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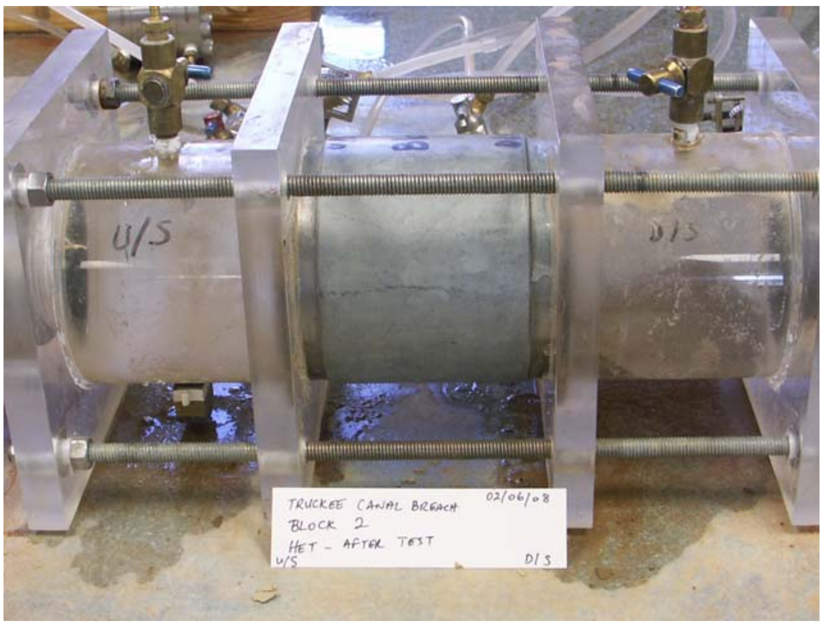
Technical Memorandum No. MERL-08-6

Results of Laboratory Physical Properties and Hole Erosion Tests, Truckee Canal Embankment Breach, Newlands Project, Nevada



U.S. Department of the Interior
Bureau of Reclamation
Technical Service Center
Denver, Colorado

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Mission Statements

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BUREAU OF RECLAMATION
Technical Service Center, Denver, Colorado
Materials Engineering and Research Laboratory, 86-68180

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Results of Laboratory Physical Properties and Hole Erosion Tests, Truckee Canal Embankment Breach, Newlands Project, Nevada

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Purpose

This laboratory test program was designed to provide data that would improve the understanding of the January 2008 breach of the Truckee Canal Embankment, a component of the Newlands Project, Nevada. The information obtained will be used in the development of a permanent repair for the area of the breach, and will facilitate the future use of the breach event as a case study by developers of new tools for evaluating embankment safety.

Hole erosion tests and physical properties tests were performed on samples obtained from the breached embankment and its foundation to determine threshold shear stresses and erosion rate coefficients applicable to potential internal erosion of the soils.

Introduction

Truckee Canal (Canal) is one of the carriage facilities of the Newlands Project, and extends 32 miles from Derby Diversion Dam southeast to Lahontan Dam. Derby Diversion Dam is located on the Truckee River, about 20 miles east of Reno, Nevada. The Canal and three tunnels on the canal route were constructed between September 1903 and November 1906. The Canal has an initial capacity of 1500 ft^3/s and an ending capacity of 900 ft^3/s [1][1]. The tunnels are 15 ft wide and 309 ft to 1521 ft long. The Canal is a Newlands Project facility which is owned by the Bureau of Reclamation (BOR) and operated and maintained by the Truckee-Carson Irrigation District (TCID). It conveys water to the Fernley and Fallon areas for agricultural use and wetlands purposes.

At about 4:30 a.m. on Saturday January 5, 2008, a breach of the canal embankment occurred in a reach of the Canal near Fernley, Nevada, about 12 miles downstream from Derby Diversion Dam [2]. The breach occurred after a 1.91-inch rainfall event the previous day in the Reno/Sparks area, which caused increased canal flows (but still 20 percent below historical maximum flows in this reach). An investigation concluded that piping due to rodent activity is the most likely cause of the failure [3]. A large complex of muskrat holes was investigated after the failure about 250 ft downstream from the breach [4]. This was the ninth known failure of the Truckee Canal embankment during the history of the project. No previous failure has occurred at this specific site.

[1] Numbers in brackets refer to entries in the references section.

Following the failure, canal water drained through the breach from both the upstream and downstream sections of the canal and inundated 500 to 600 houses in Fernley. Water depths of up to eight feet were reported at a few locations, and depths of one to four feet were common throughout one large housing development. Water from the canal continued to exit through the breach for more than nine hours before a breach plug could be dumped into place and a cofferdam placed within the canal along the downstream side of the breach.

Figure 1 shows the breach opening, about 8.5 hours after the failure occurred. The breach apparently developed and enlarged over a 2 to 3 hour period. The first report of a problem came shortly before 4:30 a.m., and the first eyewitness at the breach site reported the breach to be about 15 ft wide between 4:40-5:00 a.m., with the canal water surface only about 8 inches below the normal operating level. At 5:45 a.m. a second eyewitness estimated the breach to be 20 ft wide with flow 1 ft deep through the opening. The first eyewitness returned to the site at about 6:30-7:00 a.m. (after canal check gates had been shut to limit flow toward the breach site) and reported the breach to be larger than on his first visit, and the canal level dropped. From the photographs shown here and other information, the final breach opening is estimated to be about 18 ft deep and 25 to 35 ft wide. Immediate efforts to plug the breach prevented detailed measurements of the breach geometry.

Figure 1. — Truckee Canal breach at station 714+00, 8.5 hours after breach [4]. Canal flow is normally left to right. Material is already being pushed into the left side of the breach to form a temporary breach plug. Photo by Kenneth Parr, 1:04pm, 1-5-08.

Figures 2 and 3 show the canal embankment and foundation geology in greater detail. The canal embankment is a cut-and-fill structure, with the canal excavated into Quaternary Lahontan Lakebed deposits (Ql) composed of high fines content Silt (ML) and Silt with Sand (ML)s, with minor beds of Elastic Silt (MH) and Fat Clay (CH). The canal banks are built up from the excavated materials, founded on undisturbed lakebed deposits. The fill material at the site of the breach is about 8 ft thick.

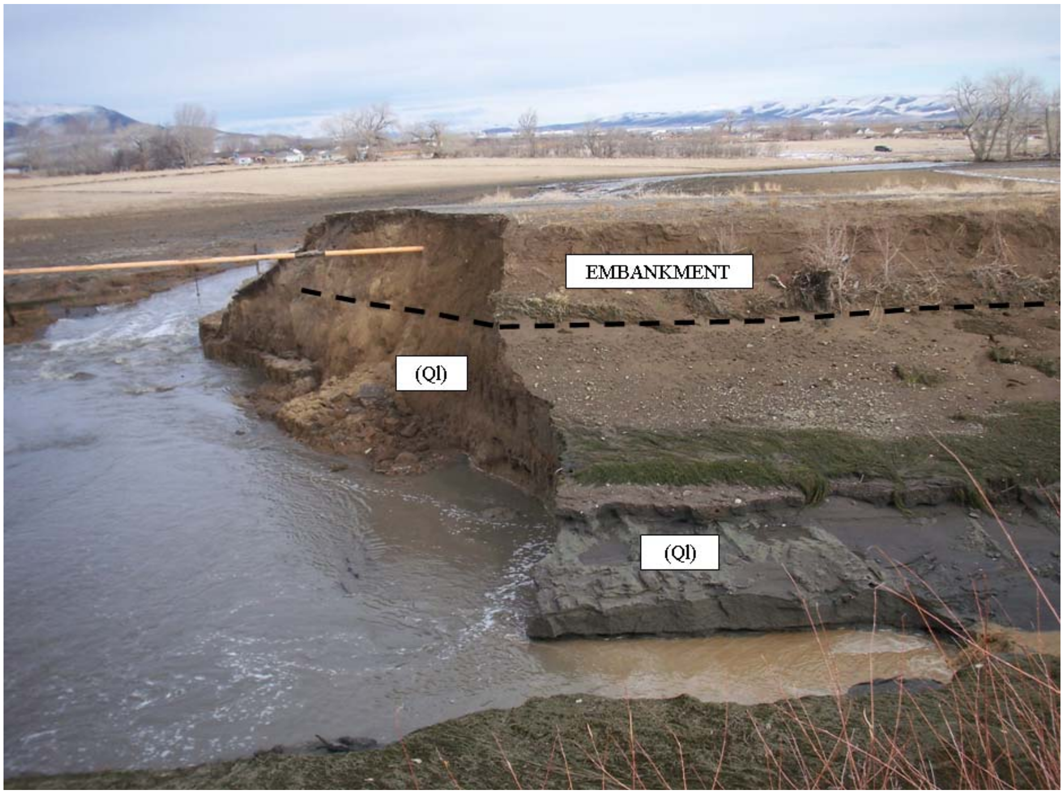

Figure 2. — Embankment and foundation layers at the breach site [4]. Photo by Kenneth Parr, 1:04pm, 1-5-08.

The original canal embankment was constructed with approximately 1.5:1 (H:V) side slopes. At the breach location, the original embankment crest width was about 8 ft and the canal depth was 15 ft. The canal has been periodically dredged through the years and the dredged material has been placed on the canal's landside embankment face as a waste berm. Grading and placing of road-base material on the embankment crest has also caused widening of the crest and steepening of the upper waterside embankment slope above the maximum water surface level in the canal. The canal embankment crest width at the time of the failure was about 20 feet.

Following initial site investigations, the Materials Engineering and Research Laboratory (MERL) received two undisturbed, waxed block samples, Blocks 1 and 2, and a sack sample, TP-07-4 at 0-6 ft, in late January 2008. Two additional sack samples, TP-07-1 at 0-7 ft, were delivered to the Denver laboratory on February 15, 2008. Both block samples were obtained from the foundation, composed of Lahontan Lakebed sediment. Block 1 was obtained 17.5 ft below the top of the embankment, with top Elevation (El.) 4181.42 ft. Block 2 was obtained from the bottom of the embankment and top of Lahontan Lakebed sediment at top El. 4187.1 ft. Sample TP-07-4 was obtained from the downstream breach face (the face shown in Fig. 3), labeled as EMB-19 [4]. Sample TP-07-1 was labeled "Ex Zone 1 East Embankment". The east embankment is the breached embankment, and these two samples are believed to be representative of the embankment fill materials, but the exact location at which these samples were collected is uncertain.

Figure 3. — Downstream view of the Truckee Canal Breach [4]. Dashed black line is the approximate contact between the canal embankment and in-place lakebed deposits (Ql). Center-left is an abandoned Sierra Pacific Power gas pipeline. Photo by Kenneth Parr, 2:07pm, 1-5-08.

Physical properties and hole erosion tests (HET) were requested to evaluate the erodibility of these soils. Testing was performed in the MERL and Reclamation's Hydraulics Laboratory located in Denver, CO. In addition to the requested tests, two submerged jet erosion tests [5] were performed on sample TP-07-1 for a supplementary evaluation of soil erodibility relative to recent laboratory tests of piping-initiated embankment breach carried out at the USDA-ARS hydraulics laboratory in Stillwater, Oklahoma. A detailed discussion of these tests and their results is provided in Appendix D.

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[2] The Canal Embankment top El. is 4195.6 ft.

Conclusions

Sample No. Block 1

- This block sample was obtained from the embankment foundation, 17.5 ft down below the top of the embankment. Top El. is 4181.4 ft and coordinates are 14,885,670 N and 2,439,533 E.

- The soil is classified as Fat Clay (CH) with a specific gravity of 2.74, Liquid Limit (LL) of 57 and Plasticity Index (PI) of 29. As-received moisture content was 47% and dry unit weight was 70 lbf/ft^3.

- Two HETs of the Block 1 undisturbed sample produced no significant erosion other than localized rounding of the entrance to the pre-drilled hole and cleanout of disturbed material from the hole. A quantitative value of the I_{HET} erosion rate index could not be determined, since no erosion was produced that lends itself to the HET analysis procedure. Based on experience with other similar materials having lower threshold shear stresses, if erosion could be produced, this material would most likely be in I_{HET} group 5 or 6 (very slow to extremely slow erosion).

Sample No. Block 2

- This sample was obtained from the foundation along the contact between the Lahontan Lakebed sediment and the Embankment where the Canal is cutting to the sediment, and it is a cut-and-fill structure. Top El. is 4187.1 ft and coordinates are 14,885,655 N and 2,439,528 E.

- The soil is classified as Silt with Sand (ML) with a specific gravity of 2.82, and LL of 42 and PI of 9. As-received moisture content was 26% and dry unit weight was 70 lbf/ft^3.

- Two HETs of this undisturbed material were conducted, one of which was successful. In the first test significant scour occurred at the entrance of the hole, but the hole itself did not enlarge significantly. The second test was successful and produced an accelerating flow rate and progressive enlargement of the hole that could be analyzed. The test indicate that this specimen was in I_{HET} group 3 (moderately fast).

Sample No. TP-07-1 at 0-7 ft

- This sample was obtained from an unspecified location in the east embankment (labeled “Ex Zone 1 East Embankment”)

- The soil is classified as Lean Clay (CL) with a specific gravity of 2.68, and LL of 42 and PI of 19. As-received moisture content was 37%. A laboratory compaction test in accordance with USBR 5500 procedure showed that the maximum dry unit weight is 99 lbf/ft^3 with an optimum moisture content of 22%.

- Four HETs of this material were conducted. All were unsuccessful. Samples were compacted 2% dry of optimum moisture content to approximately 80% of maximum dry unit weight, a condition believed to be representative of the field condition. In this condition, these samples were so weak that scour occurred and soil collapsed around the entrance and exit of the pre-drilled holes. This erosion behavior dominated all of the tests. Because none of these tests produced the intended erosion mechanism, a quantitative analysis could not be performed. Based on experience with other materials, at this compaction condition this material is likely to be in I_{HET} group 2, or possibly even group 1.

- Two submerged jet erosion tests were performed on specimens compacted similarly to the four HET specimens. Appendix D contains detailed results of these tests and a comparison to jet test results from soils used in recent laboratory tests of piping-initiated embankment breach carried out at the USDA-ARS hydraulics laboratory in Stillwater, Oklahoma. In the compaction condition tested, the TP-07-1 soil would be characterized as very erodible by the JET method. It appears to have erosion resistance midway between the soils used in the first three piping breach tests performed by ARS.

Sample No. TP-07-4 at 0-6 ft

- This sample was obtained from the embankment material zone in the downstream breach face (right side of breach opening, looking toward Fernley NV), labeled as EMB-19 [4]. The soil is classified as Lean Clay (CL) with a specific gravity of 2.69, and LL of 30 and PI of 10. As-received moisture content was 28%.

- One HET specimen was prepared at the as-received moisture content (28%), using similar compaction effort as the 4 HET specimens prepared for TP-07-1 (3 layers, 5 blows per layer). This sample did not contain enough soil to allow for a complete laboratory compaction test to determine the relationship between the dry unit weight and moisture content, but the HET specimen was probably compacted at the wet side of optimum. The resulting dry unit weight was 96 lb/ft^3. The HET was successful and indicated this sample was at the low end of I_{HET} group 4 (moderately slow erosion). The reduced erodibility of this specimen compared to the TP-07-1 specimens illustrates the dramatic effect that compaction conditions can have on erodibility.

Laboratory Test Program

Laboratory testing was performed on each of the soil samples to determine the physical properties and internal erosion potential. Testing was accomplished using procedures defined by USBR Earth Manual [6], ASTM [5], Wan and Fell [7, 8], and Reclamation's ongoing research program to further develop the HET method and compare it to other erosion testing procedures.

Sampling and Test Procedures

Field sampling was performed by BOR personnel. Two undisturbed block samples, Blocks 1 and 2, and a sack sample, TP-07-4 at 0-6 ft, were delivered to Denver in late January 2008 for testing. Two additional sack samples, TP-07-1 at 0-7 ft, were delivered to the Denver laboratory on February 15, 2008. Materials in the two sack samples, TP-07-1 and TP-07-4, were relatively similar.

The block samples 1and 2 were part of the foundation, Lahontan Lakebed sediment. Block 1 was obtained 17.5 ft down below the top of the embankment. Top Elevation (El.) is 4181.4 ft and coordinates are 14,885,670 N and 2,439,533 E. Block 2 was obtained from the bottom of the embankment and the top of the Lahontan Lakebed sediment layer. Top El. is 4187.1 ft and coordinates are 14,885,655 N and 2,439,528 E. Sample TP-07-4 was obtained from the downstream breach face (right side of breach opening looking through it toward Fernley, NV), labeled as EMB-19. Sample TP-07-1 was labeled "Ex Zone 1 East Embankment". The east embankment is the breached embankment, and the two sack samples are believed to be representative of the embankment fill materials, but the exact location of the samples is uncertain.

The following laboratory tests were performed:

- Specific Gravity of Soils (USBR 5320, Method A)
- Gradation Analysis of Gravel Size Fraction of Soils (USBR 5325)
- Gradation Analysis of Fines and Sand Size Fraction of Soils, Including Hydrometer Analysis (USBR 5330)
- Liquid Limit of Soils by the Three-Point Method (USBR 5355)
- Plastic Limit and Plasticity Index of Soils (USBR 5360)
- Laboratory Compaction of Soils – 5.5-lbm Rammer and 18-in Drop (USBR 5500)
- Moisture-Density Relations of Soils and Soil-Aggregate Mixtures Using 5.5-lb (2.49 kg) Rammer and 12-in (305-mm) Drop (ASTM D 698, Method A)
- Hole erosion test (HET), an on-going internal erosion research. A detailed current application of HET procedure is given in Appendix C.
- JET (ASTM D 5852)

The physical properties tests were performed on all samples. The laboratory compaction test (in accordance with USBR 5500) was performed only on soil from TP-07-1. HETs were performed on all soils. The HET specimens from TP-07-1 and TP-07-4 were compacted in accordance with ASTM D 698[3]. The JET test was only performed on soil from TP-07-1.

Physical Properties Testing

The physical properties tests of Blocks 1 and 2 were performed on soils trimmed from HET samples. Block 1 is classified as Fat Clay (CH) with a specific gravity of 2.74, LL of 57 and PI of 29, as-received moisture content of 47% and a dry unit weight of 70 lbf/ft^3. Block 2 is classified as Silt with Sand (ML) with a specific gravity of 2.82, LL of 42 and PI of 9, as-received moisture content of 26% and a dry unit weight of 70 lbf/ft^3.

The soil from sack sample TP-07-1 at 0-7 ft is classified as Lean Clay (CL) with a specific gravity of 2.68, LL of 42 and PI of 19, and as-received moisture content of 37%. A standard Proctor compaction test indicated that the maximum dry unit weight is 99 lbf/ft^3 with an optimum moisture content of 22%.

The soil from sack sample TP-07-4 at 0-6 ft is classified as Lean Clay (CL) with a specific gravity of 2.69, LL of 30 and PI of 10, and as-received moisture content of 28%.

The results of physical properties testing are summarized in Table 1, and test data and plots are shown in Appendix A.

Hole Erosion Testing

The HET is a laboratory test that simulates piping erosion on a small scale by passing flow through a pre-drilled hole in a test specimen. The test presumes that erosion of the material can be described by an equation of the form:

$$\dot{m} = C_e(\tau - \tau_c)$$

where $\dot{m}$ is the rate of erosion expressed as a mass per unit time per unit area, τ is the applied shear stress, τ_c is a critical or threshold shear stress needed to initiate erosion, and C_e is an erosion rate coefficient. The hydraulic gradient required to cause progressive erosion and enlargement of the pre-drilled hole is used to compute the threshold shear stress for piping erosion of the material. The rate of

[3] ASTM D 698 (Method A) differs from USBR 5500. USBR 5500 uses 1/20 ft^3 compaction mold and is based on a manual drop of 18 inches. ASTM D 698 uses a 1/30 ft^3 compaction mold and is based on a manual rammer drop of 12 inches. Both methods however, impart the same compactive effort of 12,375 ft-lbf/ft^3 to the soil specimen.

increase of the flow during progressive erosion of the hole is used to determine the erosion rate coefficient. The erosion rate coefficient is a key parameter indicating how quickly a piping erosion failure may occur, once the threshold for erosion is exceeded. The rate coefficient varies over several orders of magnitude in soils of engineering interest. Thus, for convenience, a second parameter, the Erosion Rate Index (I_{HET}) is computed:

$$I_{HET} = -\log_{10} C_e$$

I_{HET} is computed using values of C_e expressed in units of s/m.

Typical values of the I_{HET} index range from 1 to just above 6, with larger values indicating decreasing erosion rate or increasing erosion resistance. The fractional part of the index is often dropped and the test result reported as a simple integer group number for erosion resistance. Soils with group numbers less than 2 are usually so erodible that they cannot be effectively tested in the HET device because the specimen collapses immediately when wetted. Wan and Fell [7, 8], the developers of the constant-head HET, have proposed the following descriptive terms for each value of the I_{HET} index:

- I_{HET} Group 1 - Extremely rapid
- I_{HET} Group 2 - Very rapid
- I_{HET} Group 3 - Moderately rapid
- I_{HET} Group 4 - Moderately slow
- I_{HET} Group 5 - Very slow
- I_{HET} Group 6 - Extremely slow

HETs performed for this project made use of an established facility in the MERL and a new high-head facility in the hydraulics lab that was put into operation during this project. The original HET facility could apply a maximum of 1600 mm of head during the test, while the new facility can apply nearly 5400 mm of head. In our present experience using both facilities, we have not yet been able to produce progressive erosion of a specimen with an I_{HET} value greater than about 5.2.

The HET samples from the undisturbed block samples were trimmed to fit into standard 4-inch diameter, 4.584-inch high Proctor molds, except the second test from Block 1, which was trimmed to fit into a 3-inch diameter, 4.5-inch long Shelby tube (due to lack of a remaining undisturbed block of sufficient size for a standard Proctor mold). HET specimens from the sack samples were compacted into standard Proctor molds using manual compaction equipment consistent with ASTM D698.

HET samples are installed into the test apparatus which consists of upstream and downstream chambers that fit the standard molds, connected to an upstream water supply provided by an adjustable-elevation head tank, and connected to a downstream weir box that measures the flow rate during a test. Pressure transducers sense the head on the measuring weir and the differential pressure across the sample. Test data are recorded by a computerized data acquisition system.

The upstream and downstream faces of the specimens were protected by plexiglass end plates to prevent slope failures and minimize scour around the entrance and exit of the pre-drilled hole, unless otherwise noted. These end plates had 1-in diameter orifices on center, unless otherwise noted. The specimen pre-drilled hole diameter was 6.35 mm (1/4-inch) for all tests. Post-test specimen photos are shown on Figures 4 through 12.

Block 1

Two HETs of the Block 1 undisturbed sample produced no significant erosion other than localized rounding of the entrance to the pre-drilled hole and cleanout of material disturbed during drilling of the hole.

The first test was run for 10 minutes at each head (50, 100, 200, 400, 800, and 1580 mm maximum head). The slight enlargement of the hole is believed to have occurred mostly during the first minute of the test, when material disturbed during the pre-drilling operation was removed. After that time, the flow increased each time the head was increased, but remained essentially constant during each interval.

The second HET was performed in the new high-head HET facility, where a maximum head of about 5,420 mm was applied. The test was run for 10 to 15 minutes at each head (1600, 2400, 3200 mm), and for 65 minutes at the maximum head. Again, there was minimal erosion of the specimen, with the flow reaching a steady equilibrium at each increased level of head. The maximum shear stress applied to the specimen was estimated to be 1170 Pa (24.4 lbf/ft^2). A quantitative value of the I_{HET} erosion rate index could not be determined, since no significant erosion was produced.

In the original development of the HET by Wan and Fell [7, 8], tests were performed at a maximum head of 1200 mm and specimens that did not erode at this head were assumed to be in I_{HET} group 6. Recent research by Reclamation utilizing the high-head HET facility has shown that many soils that initiate erosion at heads between 1600 and 5400 mm still erode at rates consistent with I_{HET} group 4 or 5. These soils do have a very high critical stress required to initiate erosion, but that does not change their I_{HET} index value. To date, Reclamation has not tested a material that actually erodes so slowly that it can be definitely placed into I_{HET} group 6. We have tested some soils that fail to erode at 5400 mm of head, but based on our experience we believe that these soils could still be in I_{HET} group 5.

Based on our experience with other similar materials, we believe the Block 1 specimen to be an I_{HET} group 5 or 6 soil (very slow to extremely slow erosion).

Block 2

Two HETs of the Block 2 undisturbed material were performed, one of which was successful.

The first test was run for 50 minutes at 50 mm head. The flow increased for several minutes, but was stabilizing at the end of the test. Significant scour occurred at the entrance of the hole, but the hole itself did not enlarge significantly. This scour effectively shortened the hole, causing the flow to increase somewhat, but this kind of erosion cannot be analyzed to develop an I_{HET} index value. Scour at the entrance also disturbs the flow through the remainder of the hole and requires the transport of scoured material through the hole. Both of these factors make it difficult to obtain a successful test.

For the second test, several changes were made. First, we detected that the top of the trimmed specimens seemed slightly disturbed by the trimming operation, so for the second test we reversed the specimen orientation, placing the top of the specimen downstream. Then, to reduce turbulence and further minimize scour at the entrance of the hole, a plastic geotextile mesh erosion control material was installed at the upstream end of the specimen for the second test. This allowed the second test to be conducted at a higher head that would actually produce hole enlargement. The test was run for 20 minutes at 100 mm head. It was successful and produced an accelerating flow rate and progressive enlargement of the hole that could be analyzed. Scour at the entrance and exit of the hole also occurred, but did not dominate the test.

The test data were analyzed by two different methods (see Appendix C for details), and they indicated that the I_{HET} value was in the range of 3.6 to 3.8 (erosion class 3—moderately fast). The critical shear stress to initiate erosion was between 7 and 14 Pa (0.15 to 0.29 lbf/ft^2).

TP-07-1 at 0-7 ft

Four HETs and two JETs of the sample TP-07-1 were performed. All HETs were unsuccessful. Samples were compacted 2% dry of optimum moisture content to approximately 80% of maximum dry unit weight. In this condition, these samples were so weak that scour occurred and soil collapsed around the entrance and exit of the pre-drilled holes, even with end plates and the geotextile mesh installed. This erosion behavior dominated all of the tests. Because none of these tests produced the intended erosion mechanism, a quantitative analysis could not be performed. Attempts were made to increase the test head in hopes of obtaining immediately hole enlargement before scour of the entrance and exit could occur, but this was also unsuccessful.

In two of the HETs, complete breach of the specimen occurred due to scour of the hole entrance and scour at the hole exit that eventually merged. Even in these tests (one conducted at a head of 1700 mm), visible remnants of the pre-drilled hole exhibited no enlargement. It is believed that collapse of the hole entrance and the need to then transport the collapsed material through the hole probably protected the pre-drilled hole from erosion to some degree during these tests. Material scoured from the entrance also partially clogged the pre-drilled hole at times, causing the flow rate to alternately increase and decrease during these tests. These behaviors of uncontrollable entrance and exit scour versus inability to enlarge the pre-drilled hole are contradictory to some degree, and suggest at least some resistance to erosion.

Based on these observations and our experience with other materials, at this compaction condition this material is likely to be in I_{HET} group 2, or possibly even group 1.

Jet erosion tests of the TP-07-1 soil are discussed in Appendix D.

TP-07-4 at 0-6 ft

The TP-07-4 sack sample did not contain enough material to allow for a complete laboratory compaction test. As a result, most of the HET testing was performed on the other sack sample. However, one HET specimen was prepared from TP-07-4 using similar compaction effort (3 layers, 5 blows per layer, 5.5 lb rammer, 12 inch drop, compaction energy=2475 ft-lb/ft3) as was used for the TP-07-1 specimens. However, because this specimen was compacted at the as-received moisture condition, it was probably compacted in a condition that was closer to or maybe even wetter than optimum moisture content. The compacted dry density of the specimen was 96 lb/ft3, which is consistent with this observation.

The HET of this specimen was fully successful, with a nicely controlled enlargement of the hole, progressive erosion and accelerating flow at 800 mm of head, and essentially no entrance or exit scour. The I_{HET} index value was computed by two methods and was in the range of 3.9 to 4.1 (I_{HET} group 4 - moderately slow erosion). This indicates about 2 or more orders of magnitude difference in erosion rate, compared to the TP-07-1 materials compacted to 80% of maximum density at 2% dry of optimum moisture content. This test illustrates the dramatic effect that compaction conditions can have on erodibility. Hanson and Hunt (2007) [9] have demonstrated similar effects of compacted dry density and moisture content on soil erodibility measured by the JET method.

References

[1] http://www.usbr.gov/dataweb/html/newlands.html

[2] "Truckee Canal Issue Evaluation Report of Findings", Final Risk Assessment, U.S. Department of the Interior, Bureau of Reclamation, Mid-Pacific Region, Sacramento, CA, March 2008.

[3] "Truckee Canal Failure on 5 January 2008: Investigative Evaluation Report", URS, Sacramento CA, Contract 06CS204097A.

[4] "Truckee Canal Breach Station 714+00 Geologic Investigations", U.S. Department of the Interior, Bureau of Reclamation, Mid-Pacific Region, Sacramento, CA, March 2008.

[5] "Standard Test Method for Erodibility Determination of Soil in the Field or in the Laboratory by the Jet Index Method", ASTM D 5852, Vol 04.08, 2000.

[6] Earth Manual, Part 2, A Water Resources Technical Publication, 3rd Edition, U.S. Department of the Interior, Bureau of Reclamation, Denver, CO, 1990.

[7] Wan, C.F. and Fell, R., "Investigation of Rate of Erosion of Soils in Embankment Dams", Journal of Geotechnical and Geoenvironmental Engineering, Vol. 130, No 4, pp 373-380, 2004.

[8] Wan, C.F. and Fell, R., "Investigation of Internal Erosion and Piping of Soils in Embankment Dams by the Slot Erosion Test and the Hole Erosion Test", UNICIV Report No R-412, The University of New South Wales, Sydney, Australia, 2002.

[9] Hanson, G.J., and Hunt, S.L., 2007. Lessons Learned Using Laboratory Jet Method to Measure Soil Erodibility of Compacted Soils. *Applied Engineering in Agriculture*, Vol. 23, No. 3, pp. 305-312.

Tables

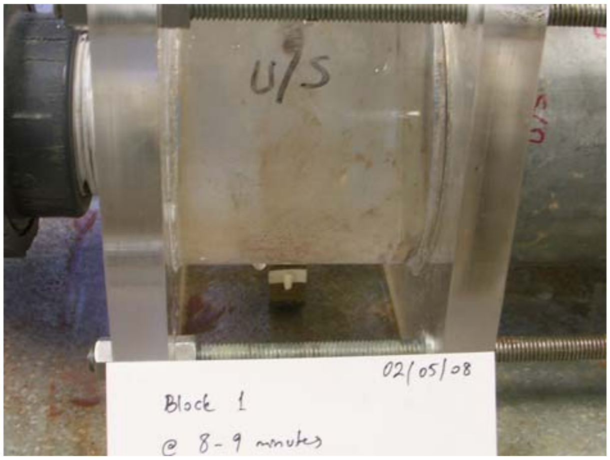
Table 1 - Physical Properties Test Results

Sample No	Initial Moisture Content	USCS Classification	Gravel	Sand	FINES			Liquid Limit LL	Plasticity Index PI	Specific Gravity
					Silt	Clay	Total Fines			
			> 4.76 mm	0.075-4.76 mm	0.005-0.075 mm	< 0.005 mm	< 0.075 mm			
	%		%	%	%	%	%	%	%	
Block 1	47.4	CH	0.0	1.2	64.0	34.8	98.8	57	29	2.74
Block 2	25.5	ML	0.7	19.7	71.3	8.3	79.6	42	9	2.82
TP-07-1 at 0-7 ft	36.6	CL	1.0	8.0	64.6	26.4	91.0	42	19	2.68
TP-07-4 at 0-6 ft	27.9	CL	1.5	37.6	42.6	18.3	60.9	30	10	2.69

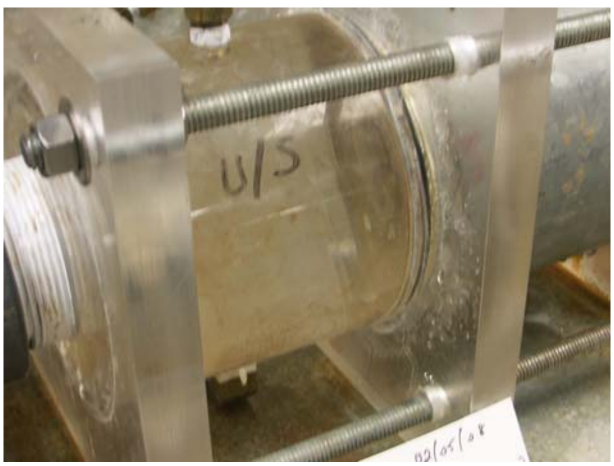
Table 2 – Hole Erosion Test Results

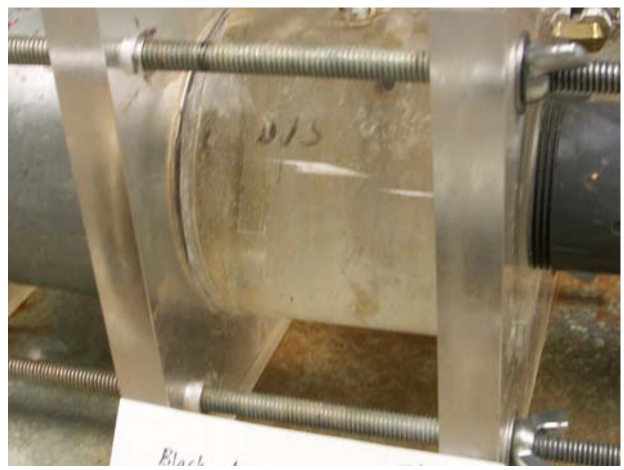
Sample No	Internal Erosion Test Sequence Number	HET Heads (mm)	Initial Moisture Content (%)	Dry Unit Weight (lbf/ft^3)	Final Hole Diameter from cast or visual observation (mm)	Internal Erosion Test Results: I_{HET}	Internal Erosion Test Results: τ_c (Pa)	Internal Erosion Test Results: Erosion Rate Group Number and Description	Comments
Block 1	HET2	50, 100, 200, 400, 800, 1580	47.4	70.1	7.2	---	> 240	---	Did not produce any significant erosion at heads up to 1580 mm.
	HET4	1600, 2400, 3200, 5350	47.4	69.6	8.5	---	> 1170	5 to 6 Very slow to extremely slow	At each increment of increased head there was a short period of flow increase, indicating localized erosion at hole entrance (streamlining the entrance) and cleanout erosion of material disturbed during drilling of the hole. However, the flow rate stabilized each time and the test never produced any significant erosion of the full length of the hole at heads up to 5350 mm.
Block 2	HET1	50	25.5	70.3	8.6	---	---	---	Significant scour in upstream part of hole, but no significant enlargement of downstream portion of hole. Flow increased due to shortening of hole, but never accelerated and was reaching a plateau at end of test (perhaps beginning to be controlled by upstream end plate). Progressive enlargement of the full length of the hole did not occur. Unable to perform analysis to compute I_{HET}.
	HET3	100	25.5	70.3	8.5	3.6 to 3.8	7 to 14	3 - Moderately rapid	Reversed test specimen to place top of block downstream (due to perceived slightly disturbed condition of upstream side of sample). Good test with accelerating flow rate throughout test, indicating progressive erosion and enlargement of the hole. There was some scour of the downstream end of the hole (last 30 mm), but analysis could be performed because there was also enlargement of the full length of the hole during the test.
TP-07-1 at 0-7 ft	HET5	50	19.9	80.6	collapsed, hole not visible	---	---	---	This test was run without end plates or upstream turbulence filter. Unable to analyze result. Bonelli analysis which does not require final diameter is also inconclusive because sample collapsed before enough data could be collected to allow a meaningful curve-fit analysis.
	HET6	60, 100, 200, 400	19.9	80.9	25 mm (hole remaining after breach of specimen due to upstream and downstream scour.	---	---	---	This test used 25 mm end plates and an upstream turbulence filter. Erosion occurred immediately at 50 mm head, but consisted mostly of scour at downstream and upstream ends. Head was increased several times in effort to produce enlargement of hole, but this was unsuccessful. The downstream headcutting and upstream scour eventually reached one another and the sample breached catastrophically, even though flow had not increased significantly up to this point (except due to increasing the head). Unable to interpret test quantitatively.
	HET7	500, 800	19.8	81.5	Length of hole was reduced, but diameter of pre-drilled hole was unchanged.	---	---	---	The sample scoured at the upstream and downstream ends, but there was no visible erosion of the pre-drilled hole. Flow increased for a few minutes at start of test, leading us to believe that hole enlargement was occurring. Flow began decreasing when material scoured from hole entrance began to block the pre-drilled hole.
	HET8	1710	19.9	81.1	Sample completely breached. Remnants of pre-drilled hole exhibit no enlargement of the hole.	---	---	---	The sample scoured at the upstream and downstream ends, and then breached through at about 5 minutes 30 seconds. When the sample was removed, remnants of the pre-drilled hole were still visible, and no erosion of the pre-drilled hole was apparent. It is thought that the need to transport large quantities of sediment through the hole (from the scouring in the entrance), probably protected the hole itself from erosion.
TP-07-4 at 0-6 ft	HET9	30, 50, 100, 200, 400, 800	27.9	96.0	9.25	3.9 to 4.1	128 to 136	4 - Moderately slow	Good test. End plates were used upstream (10 mm) and downstream (15 mm). The soil was compacted at as-received moisture content and 5 N/layer compaction effort.

Figures 4 through 12 — Hole Erosion Test Specimen Photos



(a) (b)





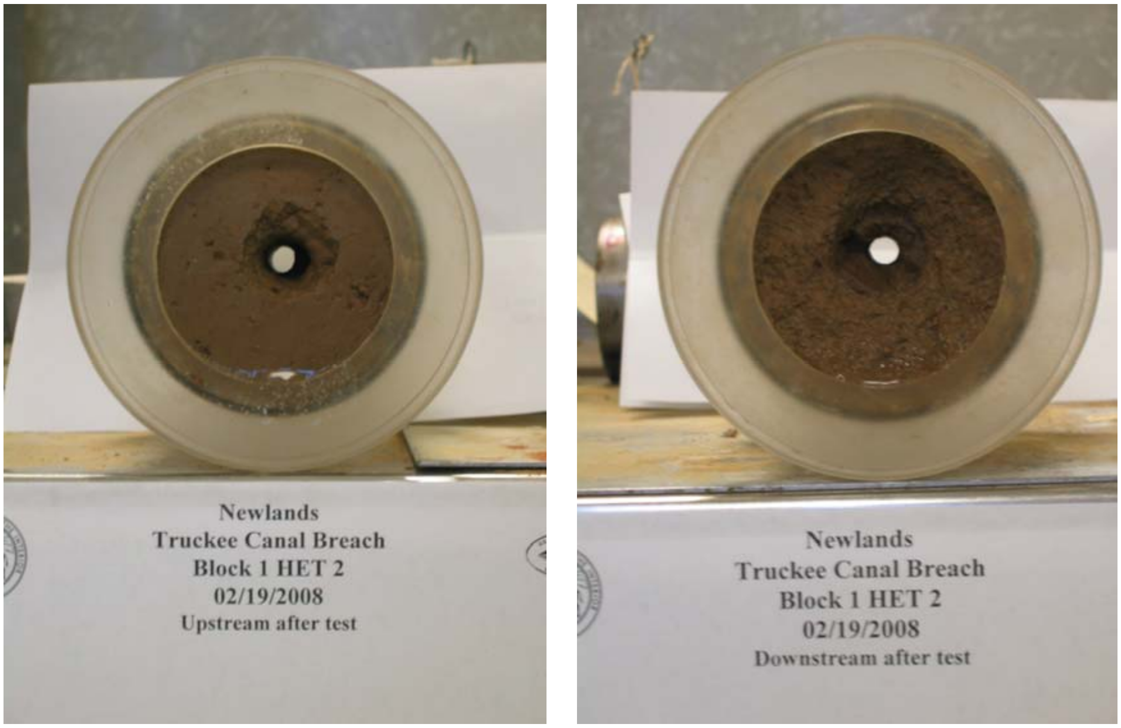
(c) (d)

Figure 4 – Block 1 HET1 specimen photos (a) U/S, and (b) D/S, 8 minutes from start of HET at head 50 mm, (c) U/S, and (d) D/S, 55 minutes from start of HET at maximum head 1580 mm

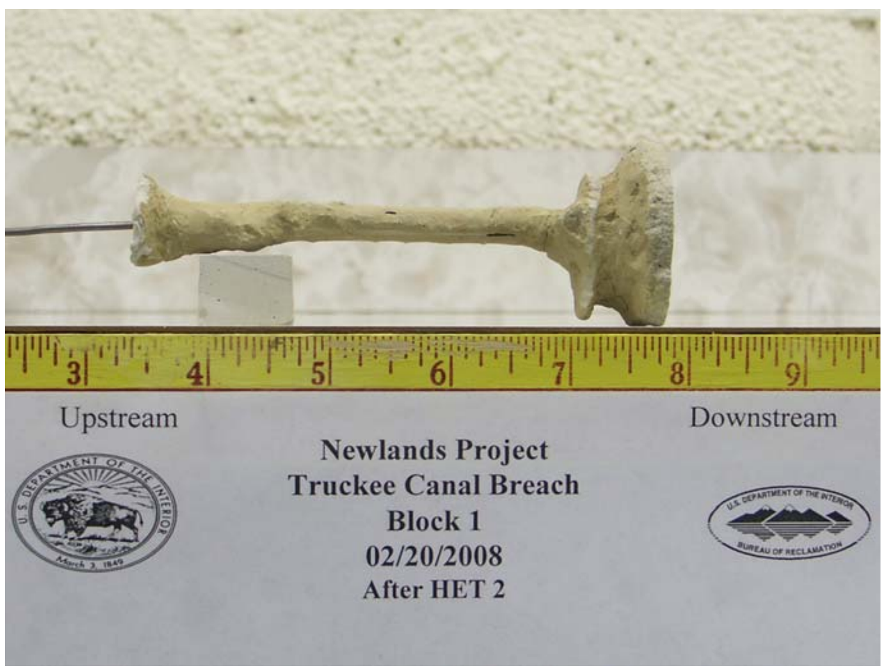
(e) (f)

(g)

Figure 4 (continued) – Block 1 HET1 specimen photos (e) U/S, (f) D/S ends showing final hole diameter, and (g) final hole cast in hydrostone. This test produced no significant erosion.

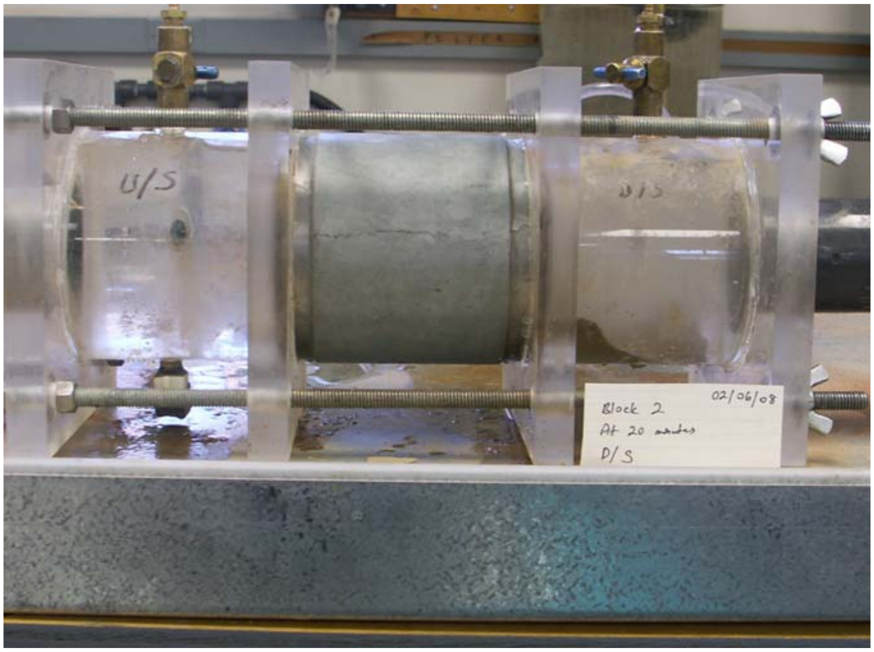


(a) (b)



(c)

Figure 5 – Block 1 HET2 specimen photos (a) U/S, (b) D/S ends showing final hole diameter, and (c) final hole cast in hydrostone. This test produced only slight erosion, not significant enough to allow determination of erodibility parameters.



(a)

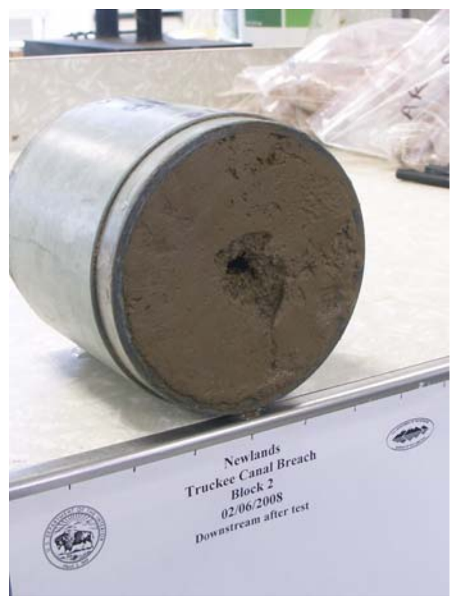
(b)

Figure 6 – Block 2 HET1 specimen photos (a) at 20 minutes from start of HET showing U/S and D/S. (b) Final hole cast in hydrostone. This test produced insufficient erosion to allow determination of erodibility parameters. Note the minimum section which is essentially unchanged from the pre-drilled hole diameter.

(c)

(d)

(e)



(f)

Figure 6 (continued) – Block 2 HET1 specimen photos (c) and (d) U/S, and (e) and (f) D/S ends after HET. Enlargement of hole was not sufficient to allow determination of erodibility parameters.

(a)

(b)

(c)

Figure 7 – Block 2 HET2 specimen photos (a) U/S, (b) D/S ends showing final hole diameter, and (c) final hole cast in hydrostone. This test was successful. Note that except for the downstream scour hole, there was relatively uniform enlargement of the full length of the pre-drilled hole.

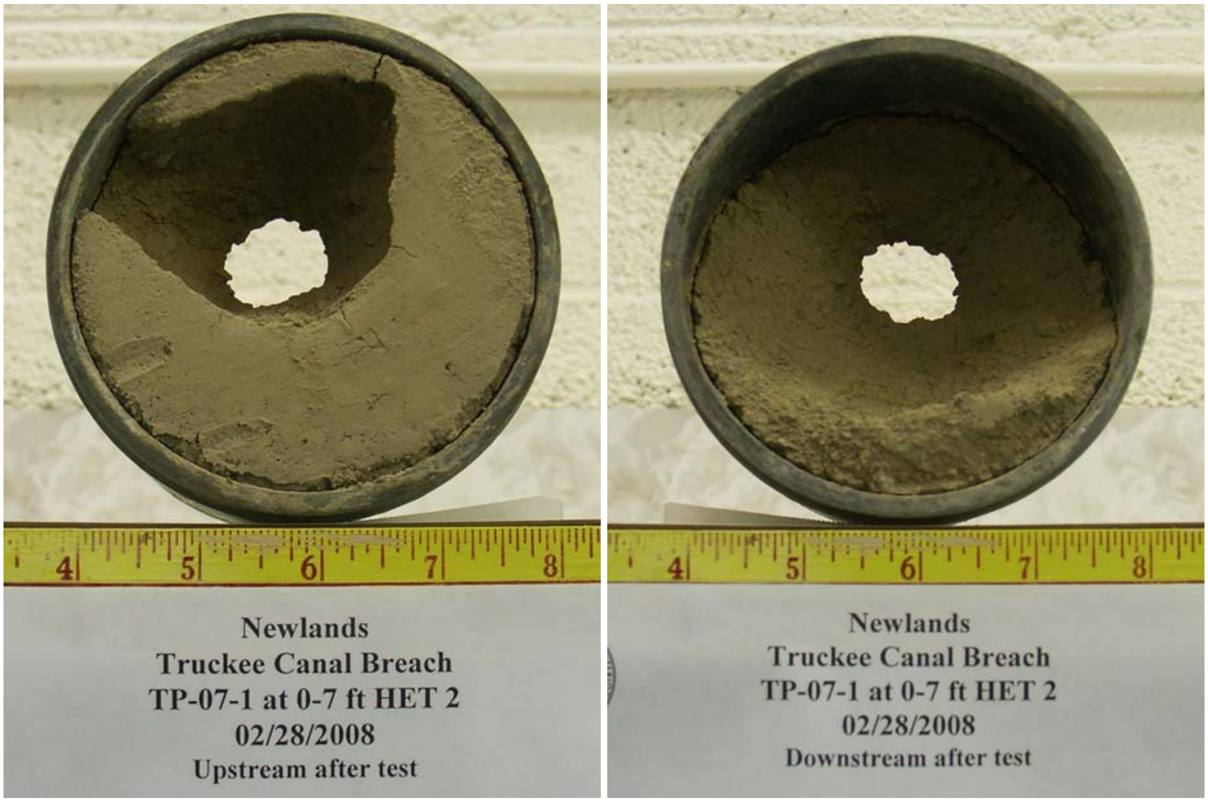
(a)

(b)

(c)

(d)

Figure 8 – TP-07-1 HET1 (a) and (b) U/S, and (c) and (d) D/S after HET. Unable to measure final hole diameter due to material collapse.



(a) (b)

Figure 9 – TP-07-1 HET2 specimen photos (a) U/S and (b) D/S after test. This test was unsuccessful due to breach of the specimen by merging of the upstream and downstream scour holes.

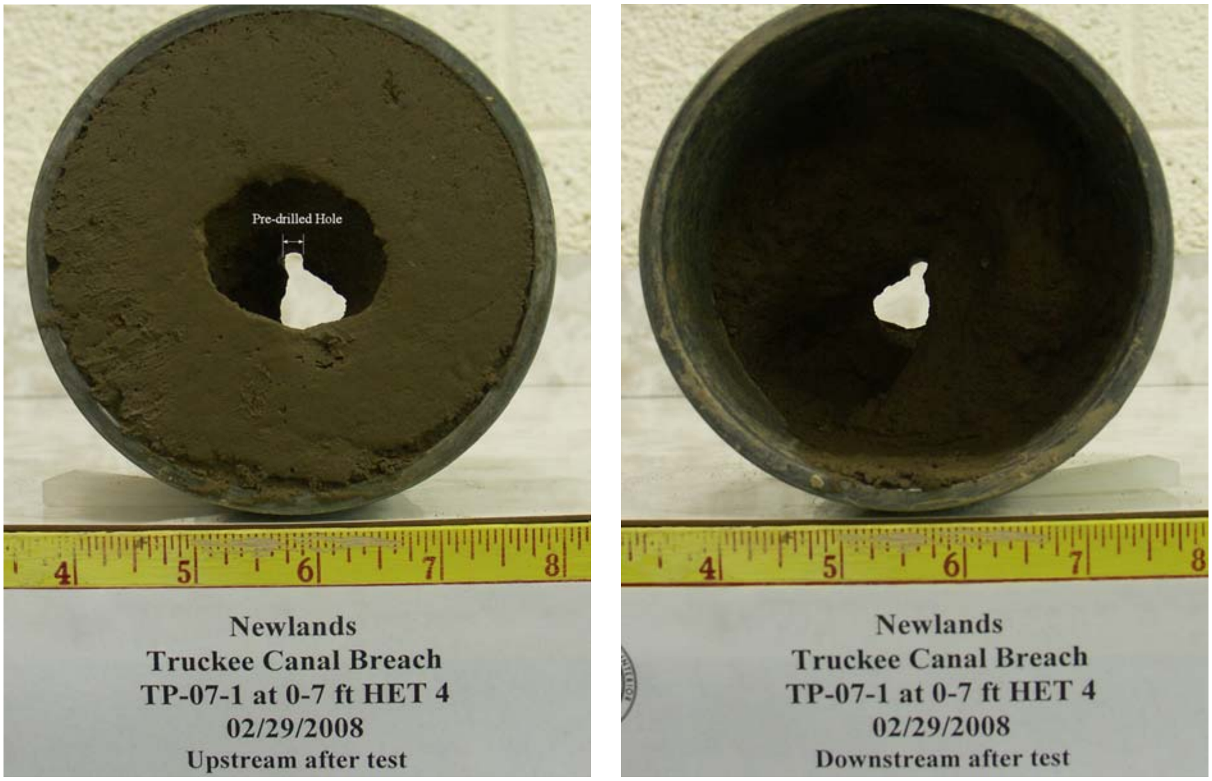
(a)

(b)

(c)

(d)

Figure 10 – TP-07-1 HET3 specimen photos (a) and (b) U/S, and (c) and (d) D/S after test. This test was unsuccessful. Scour erosion at the entrance and exit dominated the test. Note the lack of any enlargement of the small remnant of the pre-drilled hole.



(a) (b)

Figure 11 – TP-07-1 HET4 test specimen photos (a) U/S and (b) D/S after test.
This test was unsuccessful. Note the lack of any enlargement of the small remnant of the pre-drilled hole.

(a)

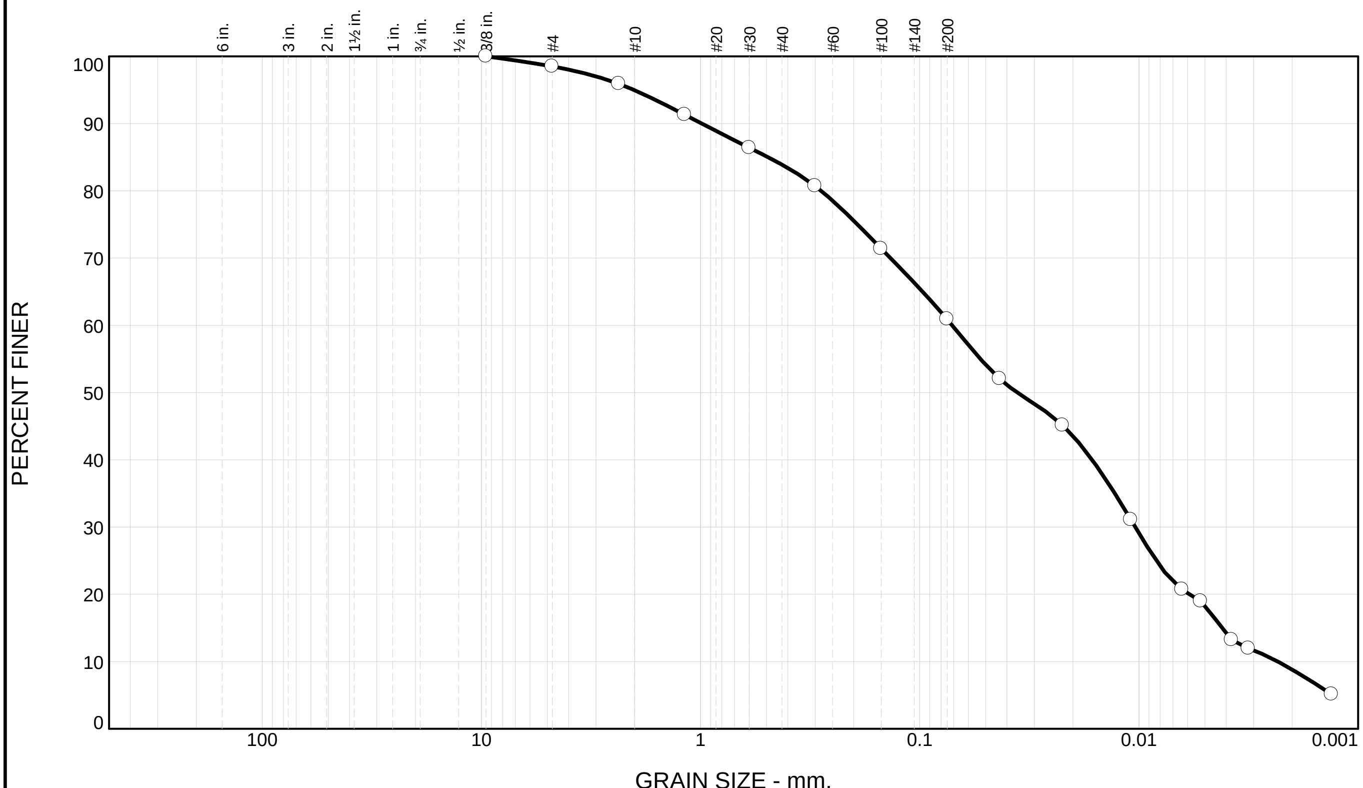
(b)

Figure 12 - TP-07-4 HET test specimen photos (a) U/S and (b) D/S after test. This test was successful.

Appendices

Appendix A: Physical Properties Test Data and Plots

Particle Size Distribution Report



% +3"	% Gravel		% Sand			% Fines	
	Coarse	Fine	Coarse	Medium	Fine	Silt	Clay
0.0	0.0	1.5	3.5	11.1	23.0	42.6	18.3

SIEVE SIZE	PERCENT FINER	SPEC.* PERCENT	PASS? (X=NO)
.375	100.0		
#4	98.5		
#8	95.9		
#16	91.3		
#30	86.4		
#50	80.7		
#100	71.4		
#200	60.9		
0.0432 mm.	52.0		
0.0223 mm.	45.1		
0.0109 mm.	31.1		
0.0064 mm.	20.7		
0.0052 mm.	19.0		
0.0038 mm.	13.2		
0.0032 mm.	11.9		
0.0013 mm.	5.1		

* (no specification provided)

Soil Description

Sandy lean clay

Atterberg Limits

PL= 21 LL= 30 PI= 10

Coefficients

D_{85}= 0.4926 D_{60}= 0.0711 D_{50}= 0.0359
D_{30}= 0.0104 D_{15}= 0.0042 D_{10}= 0.0023
C_u= 30.56 C_c= 0.65

Classification

USCS= CL AASHTO= A-4(3)

Remarks

Initial Moisture Content=27.9%
Specific Gravity=2.69

Sample No.: TP-07-4 (Test 1of2) **Source of Sample:** **Date:** 02/10/2008
Location: EMB-19, D/S Breach Face **Elev./Depth:** 0-6 ft

BUREAU OF RECLAMATION

Client: Geotechnical Services Division, TSC, Denver, CO
Project: Newlands
Project No: **Figure**

Tested By: M. Jones/Z. Erdogan **Checked By:** Z. Erdogan

GRAIN SIZE DISTRIBUTION TEST DATA

2/12/2008

Client: Geotechnical Services Division, TSC, Denver, CO
Project: Newlands
Location: EMB-19, D/S Breach Face
Depth: 0-6 ft **Sample Number:** TP-07-4 (Test 1of2)
Material Description: Sandy lean clay
Date: 02/10/2008 **PL:** 21 **LL:** 30 **PI:** 10
USCS Classification: CL **AASHTO Classification:** A-4(3)
Testing Remarks: Initial Moisture Content=27.9%
Specific Gravity=2.69
Tested by: M. Jones/Z. Erdogan **Checked by:** Z. Erdogan

Sieve Test Data

Sieve Opening Size	Percent Finer
3	
1.5	
.75	
.375	100.0
#4	98.5
#8	95.9
#16	91.3
#30	86.4
#50	80.7
#100	71.4
#200	60.9

Hydrometer Test Data

Hydrometer test uses material passing #4
Percent passing #4 based upon complete sample = 98.5
Weight of hydrometer sample =56.4
Automatic temperature correction
Composite correction (fluid density and meniscus height) at 20 deg. C = -6.0
Meniscus correction only = 0.0
Specific gravity of solids = 2.69
Hydrometer type = 152H
Hydrometer effective depth equation: L = 16.294964 - 0.164 **x Rm**

Elapsed Time (min.)	Temp. (deg. C.)	Actual Reading	Corrected Reading	K	Rm	Eff. Depth	Diameter (mm.)	Percent Finer
1.00	20.5	36.0	30.1	0.0134	36.0	10.4	0.0432	52.0
4.00	20.5	32.0	26.1	0.0134	32.0	11.0	0.0223	45.1
19.00	20.0	24.0	18.0	0.0135	24.0	12.4	0.0109	31.1
60.00	20.0	18.0	12.0	0.0135	18.0	13.3	0.0064	20.7
90.00	20.0	17.0	11.0	0.0135	17.0	13.5	0.0052	19.0
180.00	19.9	13.7	7.6	0.0135	13.7	14.0	0.0038	13.2
260.00	19.7	13.0	6.9	0.0135	13.0	14.2	0.0032	11.9
1545.00	20.0	9.0	3.0	0.0135	9.0	14.8	0.0013	5.1

Hydrometer Test Data (continued)

Elapsed Time (min.)	Temp. (deg. C.)	Actual Reading	Corrected Reading	K	Rm	Eff. Depth	Diameter (mm.)	Percent Finer

Fractional Components

Cobbles	Gravel			Sand				Fines		
	Coarse	Fine	Total	Coarse	Medium	Fine	Total	Silt	Clay	Total
0.0	0.0	1.5	1.5	3.5	11.1	23.0	37.6	42.6	18.3	60.9

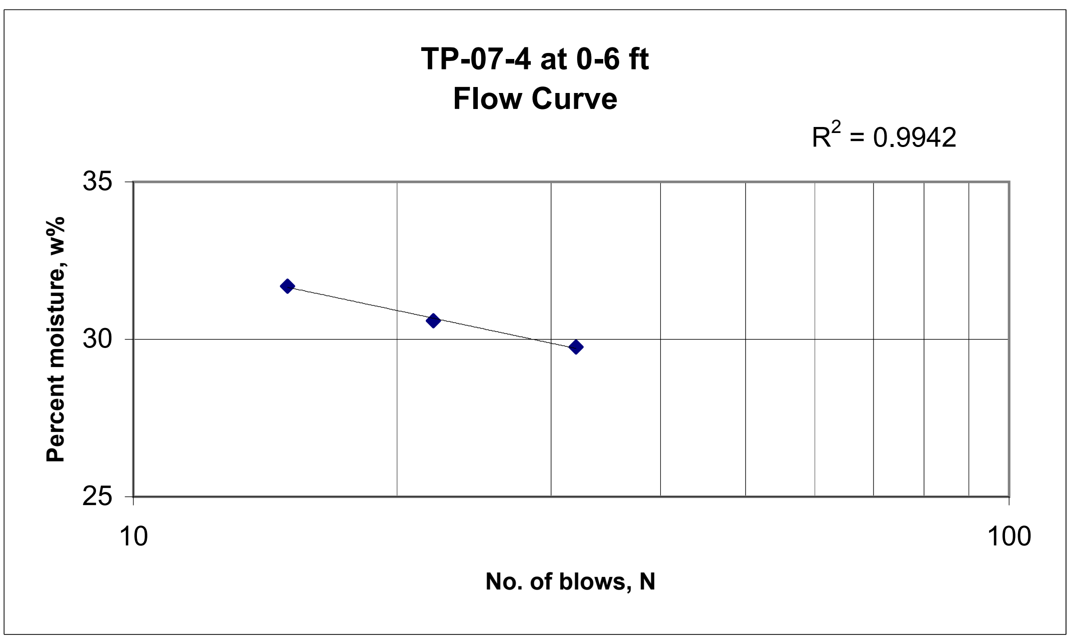
D_{10}	D_{15}	D_{20}	D_{30}	D_{50}	D_{60}	D_{80}	D_{85}	D_{90}	D_{95}
0.0023	0.0042	0.0058	0.0104	0.0359	0.0711	0.2818	0.4926	0.9880	2.0160

Fineness Modulus	C_u	C_c
0.76	30.56	0.65

Soil Consistency Test (Three-Point Liquid Limit Method)

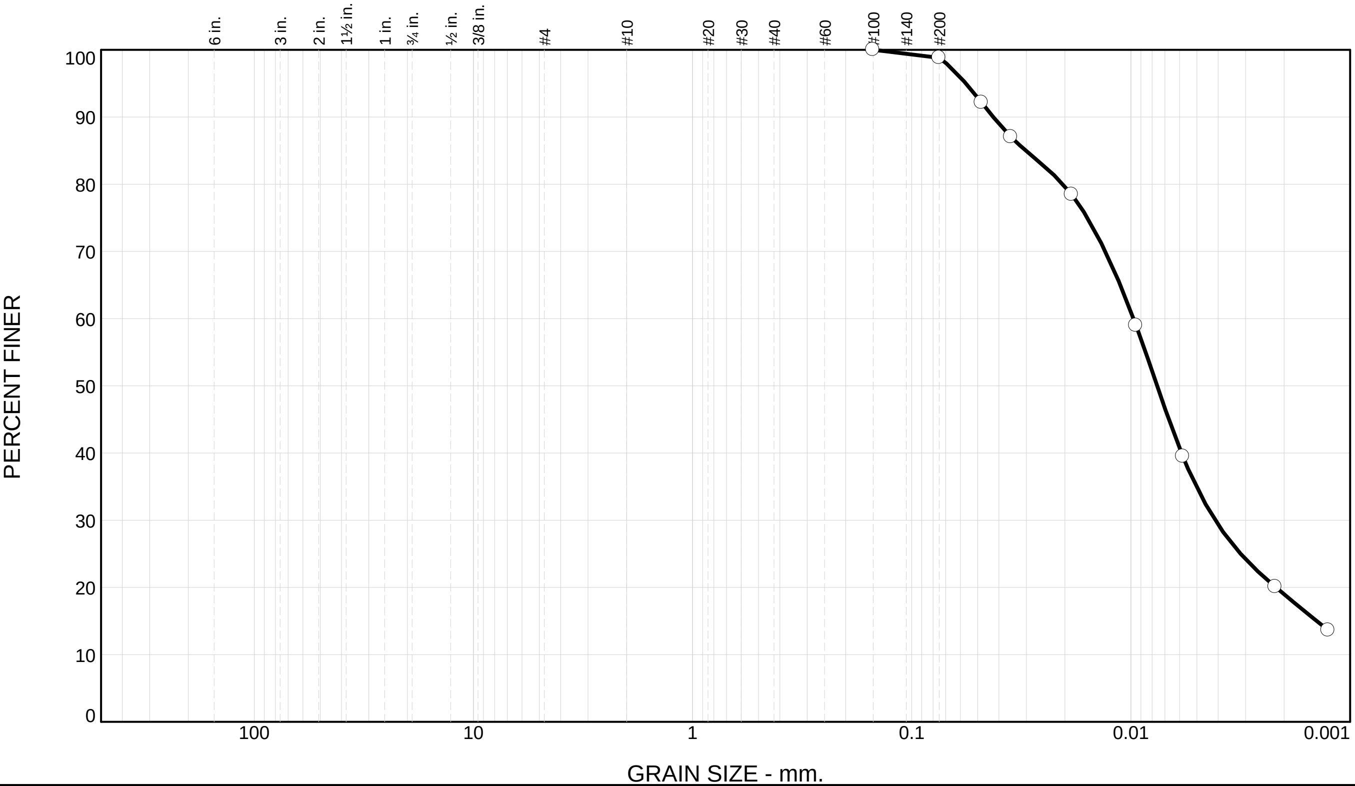
Sample No.	TP-07-4 at 0-6 ft				
Location	EMB-19, D/S Breach Face				
Feature	Truckee Canal Breach				
Project	Newlands				
Date	2/8/2008				
Test	Plastic Limit		Liquid Limit		
Trial No.	1	2	1	2	3
Dish No.	99	116	S-29	S-68	S-30
No. of blows	N/A	N/A	15	22	32
Mass of dish+wet soil (g)	13.720	12.714	17.844	17.948	20.420
Mass of dish+dry soil (g)	12.437	11.500	15.541	15.692	17.976
Mass of dish (g)	6.276	5.679	8.275	8.316	9.762
Mass of water (g)	1.283	1.214	2.303	2.256	2.444
Mass of dry soil (g)	6.161	5.821	7.266	7.376	8.214
% moisture	20.8	20.9	31.7	30.6	29.8
Average plastic limit	21				

LL = 30.34 **PL = 20.84** **PI = 9.50** **Fi = -5.9**



Remarks:

Particle Size Distribution Report



% +3"	% Gravel		% Sand			% Fines	
	Coarse	Fine	Coarse	Medium	Fine	Silt	Clay
0.0	0.0	0.0	0.0	0.0	1.2	64.0	34.8

SIEVE SIZE	PERCENT FINER	SPEC.* PERCENT	PASS? (X=NO)
#100	100.0		
#200	98.8		
0.0480 mm.	92.2		
0.0352 mm.	87.0		
0.0186 mm.	78.5		
0.0095 mm.	59.0		
0.0058 mm.	39.5		
0.0022 mm.	20.1		
0.0013 mm.	13.6		

* (no specification provided)

Soil Description

Fat clay

Atterberg Limits

PL= 28 LL= 57 PI= 29

Coefficients

D_{85}= 0.0302 D_{60}= 0.0097 D_{50}= 0.0076
D_{30}= 0.0041 D_{15}= 0.0014 D_{10}=
C_u= C_c=

Classification

USCS= CH AASHTO= A-7-6(34)

Remarks

Initial Moisture Content=47.4%
Specific Gravity=2.74

Sample No.: Block 1 **Source of Sample:** **Date:** 02/13/2008
Location: **Elev./Depth:**

BUREAU OF RECLAMATION

Client: Geotechnical Services Division, TSC, Denver, CO
Project: Newlands
Project No: **Figure**

Tested By: M. Jones/Z. Erdogan **Checked By:** Z. Erdogan

GRAIN SIZE DISTRIBUTION TEST DATA

2/13/2008

Client: Geotechnical Services Division, TSC, Denver, CO
Project: Newlands
Sample Number: Block 1
Material Description: Fat clay
Date: 02/13/2008 **PL:** 28 **LL:** 57 **PI:** 29
USCS Classification: CH **AASHTO Classification:** A-7-6(34)
Testing Remarks: Initial Moisture Content=47.4%
Specific Gravity=2.74
Tested by: M. Jones/Z. Erdogan **Checked by:** Z. Erdogan

Sieve Test Data

Sieve Opening Size	Percent Finer
3	
1.5	
.75	
.375	
#4	
#8	
#16	
#30	
#50	
#100	100.0
#200	98.8

Hydrometer Test Data

Hydrometer test uses material passing #4
Percent passing #4 based upon complete sample = 100.0
Weight of hydrometer sample =57.3
Automatic temperature correction
Composite correction (fluid density and meniscus height) at 20 deg. C = -6.0
Meniscus correction only = 0.0
Specific gravity of solids = 2.74
Hydrometer type = 152H
Hydrometer effective depth equation: L = 16.294964 - 0.164 **x Rm**

Elapsed Time (min.)	Temp. (deg. C.)	Actual Reading	Corrected Reading	K	Rm	Eff. Depth	Diameter (mm.)	Percent Finer
0.50	19.5	60.0	53.9	0.0134	60.0	6.5	0.0480	92.2
1.00	19.5	57.0	50.9	0.0134	57.0	6.9	0.0352	87.0
4.00	19.5	52.0	45.9	0.0134	52.0	7.8	0.0186	78.5
19.00	20.0	40.5	34.5	0.0133	40.5	9.7	0.0095	59.0
60.00	20.5	29.0	23.1	0.0132	29.0	11.5	0.0058	39.5
492.00	19.9	17.8	11.7	0.0133	17.8	13.4	0.0022	20.1
1560.00	20.0	14.0	8.0	0.0133	14.0	14.0	0.0013	13.6

Fractional Components

Cobbles	Gravel			Sand				Fines		
	Coarse	Fine	Total	Coarse	Medium	Fine	Total	Silt	Clay	Total
0.0	0.0	0.0	0.0	0.0	0.0	1.2	1.2	64.0	34.8	98.8

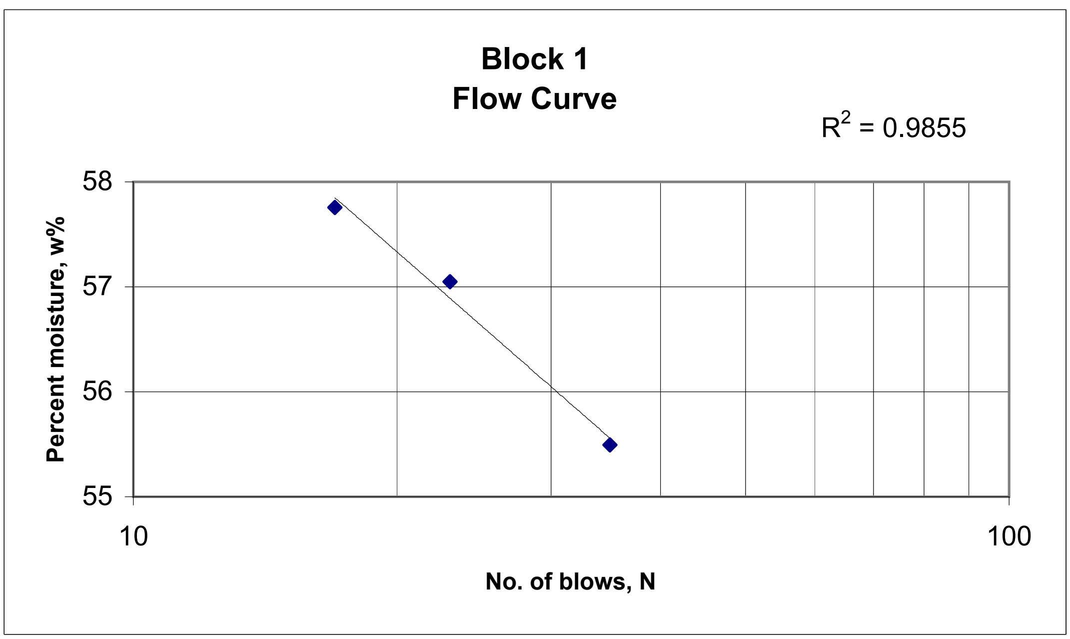
D_{10}	D_{15}	D_{20}	D_{30}	D_{50}	D_{60}	D_{80}	D_{85}	D_{90}	D_{95}
	0.0014	0.0022	0.0041	0.0076	0.0097	0.0204	0.0302	0.0425	0.0567

Fineness Modulus
0.00

Soil Consistency Test (Three-Point Liquid Limit Method)

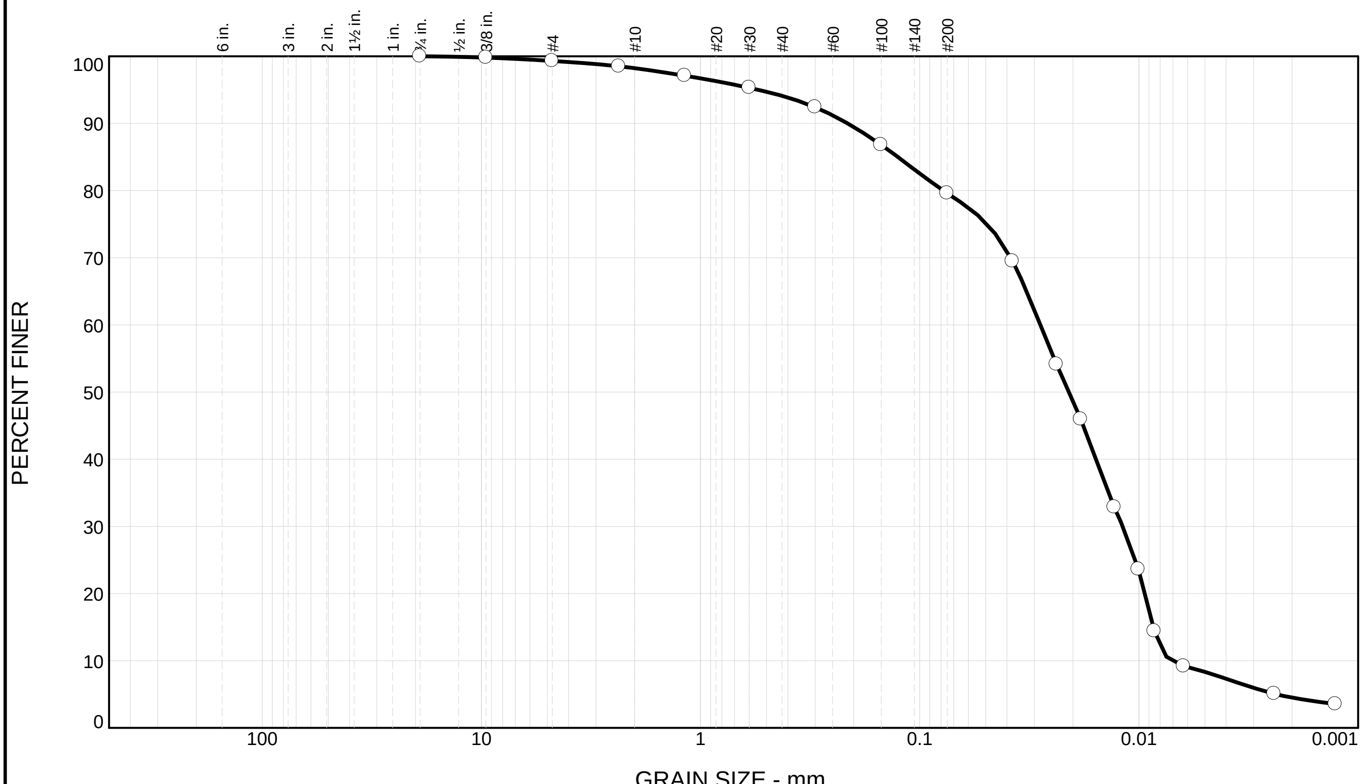
Sample No.	Block 1				
Location					
Feature	Truckee Canal Breach				
Project	Newlands				
Date	2/12/2008				
Test	Plastic Limit		Liquid Limit		
Trial No.	1	2	1	2	3
Dish No.	54	63	87	62	85
No. of blows	N/A	N/A	17	23	35
Mass of dish+wet soil (g)	11.841	12.268	15.851	15.183	16.140
Mass of dish+dry soil (g)	10.606	10.945	12.336	11.926	12.684
Mass of dish (g)	6.144	6.167	6.250	6.217	6.456
Mass of water (g)	1.235	1.323	3.515	3.257	3.456
Mass of dry soil (g)	4.462	4.778	6.086	5.709	6.228
% moisture	27.7	27.7	57.8	57.1	55.5
Average plastic limit	28				

LL = 56.6 **PL = 27.7** **PI = 28.9** **Fi = -7.3**



Remarks:

Particle Size Distribution Report



% +3"	% Gravel		% Sand			% Fines	
	Coarse	Fine	Coarse	Medium	Fine	Silt	Clay
0.0	0.0	0.7	1.1	4.1	14.5	71.3	8.3

SIEVE SIZE	PERCENT FINER	SPEC.* PERCENT	PASS? (X=NO)
.75	100.0		
.375	99.8		
#4	99.3		
#8	98.5		
#16	97.1		
#30	95.3		
#50	92.4		
#100	86.8		
#200	79.6		
0.0377 mm.	69.5		
0.0238 mm.	54.1		
0.0184 mm.	45.9		
0.0130 mm.	32.8		
0.0101 mm.	23.6		
0.0085 mm.	14.4		
0.0062 mm.	9.2		
0.0024 mm.	5.1		
0.0013 mm.	3.5		

* (no specification provided)

Soil Description

Silt with sand

Atterberg Limits

PL= 34 LL= 42 PI= 9

Coefficients

D_{85}= 0.1260 D_{60}= 0.0282 D_{50}= 0.0209
D_{30}= 0.0118 D_{15}= 0.0086 D_{10}= 0.0072
C_u= 3.92 C_c= 0.69

Classification

USCS= ML AASHTO= A-5(8)

Remarks

Initial Moisture Content=25.5%
Specific Gravity=2.82

Sample No.: Block 2 **Source of Sample:** **Date:** 02/13/2008
Location: **Elev./Depth:**

BUREAU OF RECLAMATION

Client: Geotechnical Services Division, TSC, Denver, CO
Project: Newlands
Project No: **Figure**

Tested By: M. Jones/Z. Erdogan **Checked By:** Z. Erdogan

GRAIN SIZE DISTRIBUTION TEST DATA

2/13/2008

Client: Geotechnical Services Division, TSC, Denver, CO
Project: Newlands
Sample Number: Block 2
Material Description: Silt with sand
Date: 02/13/2008 **PL:** 34 **LL:** 42 **PI:** 9
USCS Classification: ML **AASHTO Classification:** A-5(8)
Testing Remarks: Initial Moisture Content=25.5%
Specific Gravity=2.82
Tested by: M. Jones/Z. Erdogan **Checked by:** Z. Erdogan

Sieve Test Data

Sieve Opening Size	Percent Finer
3	
1.5	
.75	100.0
.375	99.8
#4	99.3
#8	98.5
#16	97.1
#30	95.3
#50	92.4
#100	86.8
#200	79.6

Hydrometer Test Data

Hydrometer test uses material passing #4
Percent passing #4 based upon complete sample = 99.3
Weight of hydrometer sample =93.54
Automatic temperature correction
Composite correction (fluid density and meniscus height) at 20 deg. C = -6.0
Meniscus correction only = 0.0
Specific gravity of solids = 2.82
Hydrometer type = 152H
Hydrometer effective depth equation: L = 16.294964 **-** 0.164 **x Rm**

Elapsed Time (min.)	Temp. (deg. C.)	Actual Reading	Corrected Reading	K	Rm	Eff. Depth	Diameter (mm.)	Percent Finer
0.50	19.5	74.0	67.9	0.0131	74.0	4.2	0.0377	69.5
2.00	19.5	59.0	52.9	0.0131	59.0	6.6	0.0238	54.1
4.00	19.5	51.0	44.9	0.0131	51.0	7.9	0.0184	45.9
10.00	20.5	38.0	32.1	0.0129	38.0	10.1	0.0130	32.8
19.00	20.5	29.0	23.1	0.0129	29.0	11.5	0.0101	23.6
30.00	20.5	20.0	14.1	0.0129	20.0	13.0	0.0085	14.4
60.00	20.0	15.0	9.0	0.0130	15.0	13.8	0.0062	9.2
420.00	20.0	11.0	5.0	0.0130	11.0	14.5	0.0024	5.1
1545.00	20.0	9.5	3.5	0.0130	9.5	14.7	0.0013	3.5

Fractional Components

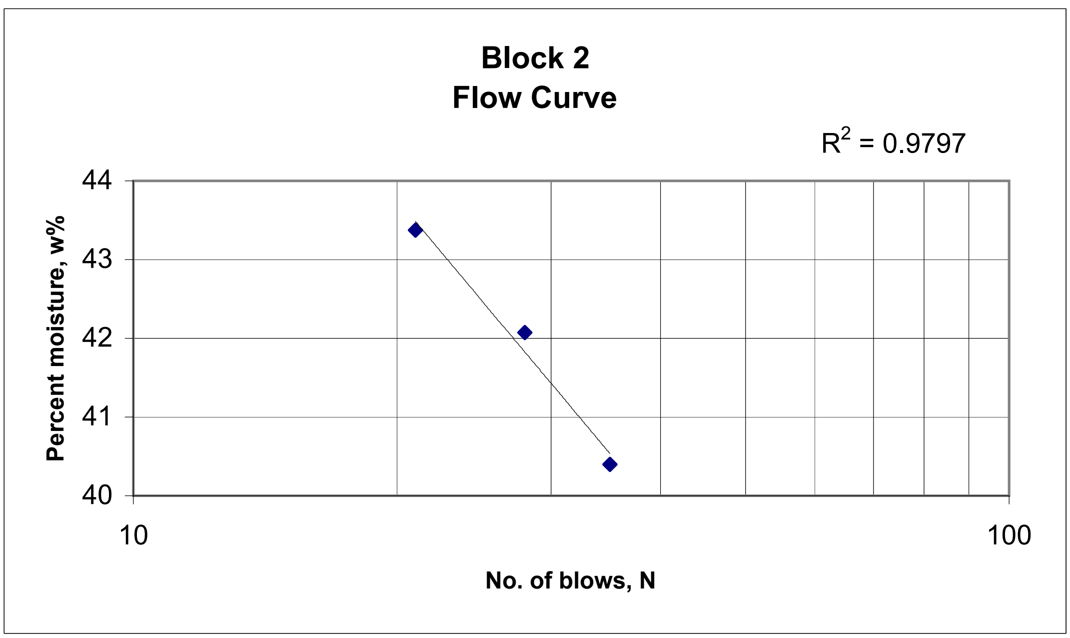
Cobbles	Gravel			Sand				Fines		
	Coarse	Fine	Total	Coarse	Medium	Fine	Total	Silt	Clay	Total
0.0	0.0	0.7	0.7	1.1	4.1	14.5	19.7	71.3	8.3	79.6

D_{10}	D_{15}	D_{20}	D_{30}	D_{50}	D_{60}	D_{80}	D_{85}	D_{90}	D_{95}
0.0072	0.0086	0.0094	0.0118	0.0209	0.0282	0.0782	0.1260	0.2134	0.5453

Fineness Modulus	C_u	C_c
0.31	3.92	0.69

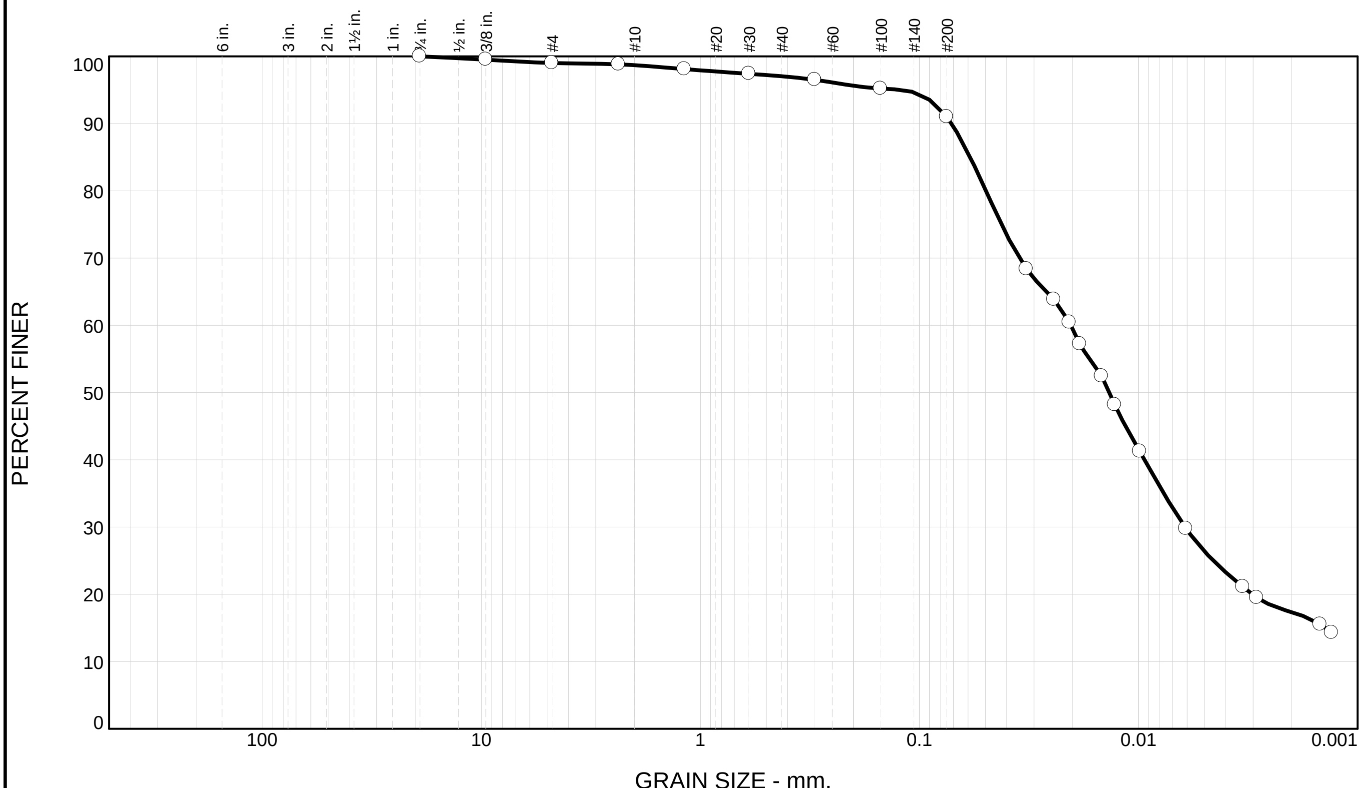
Soil Consistency Test (Three-Point Liquid Limit Method)					
Sample No.	Block 2				
Location					
Feature	Truckee Canal Breach				
Project	Newlands				
Date	2/12/2008				
Test	Plastic Limit		Liquid Limit		
Trial No.	1	2	1	2	3
Dish No.	S-12	104	89	72	56
No. of blows	N/A	N/A	21	28	35
Mass of dish+wet soil (g)	15.830	14.498	19.546	20.858	16.854
Mass of dish+dry soil (g)	14.297	12.458	15.518	16.532	13.841
Mass of dish (g)	9.784	6.443	6.232	6.249	6.383
Mass of water (g)	1.533	2.040	4.028	4.326	3.013
Mass of dry soil (g)	4.513	6.015	9.286	10.283	7.458
% moisture	34.0	33.9	43.4	42.1	40.4
Average plastic limit	34				

LL = 42.48 **PL = 33.94** **PI = 8.54** **Fi = -13.3**



Remarks:

Particle Size Distribution Report



% +3"	% Gravel		% Sand			% Fines	
	Coarse	Fine	Coarse	Medium	Fine	Silt	Clay
0.0	0.0	1.0	0.3	1.7	6.0	64.6	26.4

SIEVE SIZE	PERCENT FINER	SPEC.* PERCENT	PASS? (X=NO)
.75	100.0		
.375	99.5		
#4	99.0		
#8	98.8		
#16	98.1		
#30	97.4		
#50	96.5		
#100	95.2		
#200	91.0		
0.0324 mm.	68.4		
0.0243 mm.	63.8		
0.0207 mm.	60.4		
0.0185 mm.	57.2		
0.0147 mm.	52.4		
0.0128 mm.	48.2		
0.0099 mm.	41.2		
0.0061 mm.	29.8		
0.0033 mm.	21.1		
0.0029 mm.	19.5		
0.0015 mm.	15.5		
0.0013 mm.	14.3		

* (no specification provided)

Soil Description

Lean clay

Atterberg Limits

PL= 23 LL= 42 PI= 19

Coefficients

D_{85}= 0.0586 D_{60}= 0.0204 D_{50}= 0.0136
D_{30}= 0.0061 D_{15}= 0.0014 D_{10}=
C_u= C_c=

Classification

USCS= CL AASHTO= A-7-6(19)

Remarks

As-received Moisture Content=36.6%
Specific Gravity=2.68

Sample No.: TP-07-1 **Source of Sample:** **Date:** 02/19/08
Location: East Embankment **Elev./Depth:** 0-7 ft

BUREAU OF RECLAMATION

Client: Geotechnical Services Division, TSC, Denver, CO
Project: Newlands

Project No: **Figure**

Tested By: Z. Erdogan

GRAIN SIZE DISTRIBUTION TEST DATA

2/19/2008

Client: Geotechnical Services Division, TSC, Denver, CO
Project: Newlands
Location: East Embankment
Depth: 0-7 ft
Sample Number: TP-07-1
Material Description: Lean clay
Date: 02/19/08 **PL:** 23 **LL:** 42 **PI:** 19
USCS Classification: CL **AASHTO Classification:** A-7-6(19)
Testing Remarks: As-received Moisture Content=36.6%
Specific Gravity=2.68
Tested by: Z. Erdogan

Sieve Test Data

Sieve Opening Size	Percent Finer
3	
1.5	
.75	100.0
.375	99.5
#4	99.0
#8	98.8
#16	98.1
#30	97.4
#50	96.5
#100	95.2
#200	91.0

Hydrometer Test Data

Hydrometer test uses material passing #4
Percent passing #4 based upon complete sample = 99.0
Weight of hydrometer sample =86.72
Automatic temperature correction
Composite correction (fluid density and meniscus height) at 20 deg. C = -6
Meniscus correction only = 0.0
Specific gravity of solids = 2.68
Hydrometer type = 152H
Hydrometer effective depth equation: L = 16.294964 - 0.164 **x Rm**

Elapsed Time (min.)	Temp. (deg. C.)	Actual Reading	Corrected Reading	K	Rm	Eff. Depth	Diameter (mm.)	Percent Finer
1.00	16.8	67.0	60.3	0.0141	67.0	5.3	0.0324	68.4
2.00	16.8	63.0	56.3	0.0141	63.0	6.0	0.0243	63.8
3.00	16.8	60.0	53.3	0.0141	60.0	6.5	0.0207	60.4
4.00	16.7	57.2	50.5	0.0141	57.2	6.9	0.0185	57.2
7.00	16.6	53.0	46.2	0.0141	53.0	7.6	0.0147	52.4
10.00	16.4	49.3	42.5	0.0142	49.3	8.2	0.0128	48.2
19.00	16.3	43.2	36.4	0.0142	43.2	9.2	0.0099	41.2
60.00	15.8	33.2	26.3	0.0143	33.2	10.9	0.0061	29.8
222.00	15.6	25.6	18.6	0.0143	25.6	12.1	0.0033	21.1
305.00	15.5	24.2	17.2	0.0143	24.2	12.3	0.0029	19.5

Hydrometer Test Data (continued)

Elapsed Time (min.)	Temp. (deg. C.)	Actual Reading	Corrected Reading	K	Rm	Eff. Depth	Diameter (mm.)	Percent Finer
1200.00	15.9	20.6	13.7	0.0142	20.6	12.9	0.0015	15.5
1515.00	16.8	19.3	12.6	0.0141	19.3	13.1	0.0013	14.3

Fractional Components

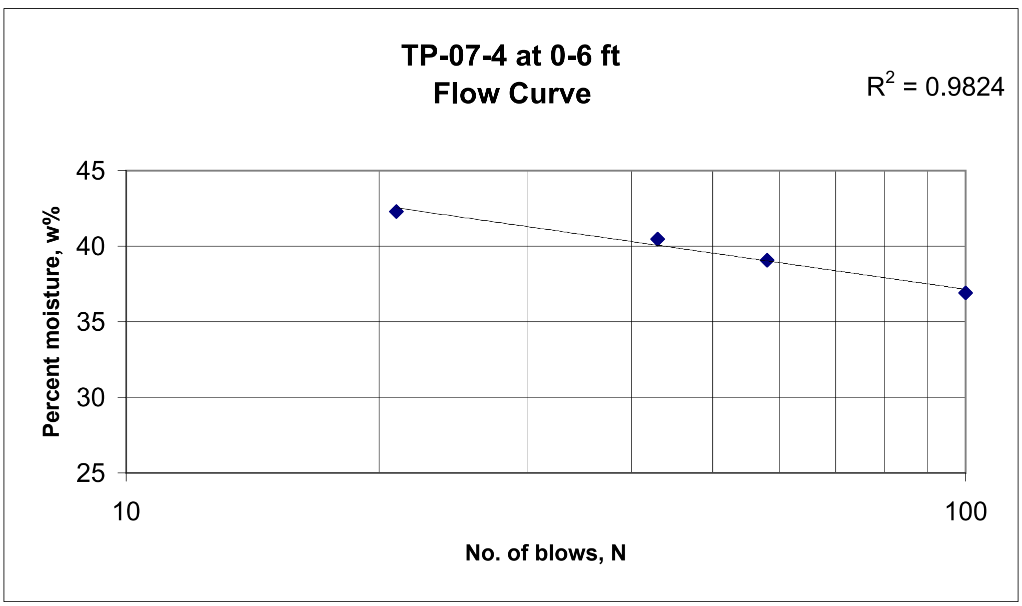
Cobbles	Gravel			Sand				Fines		
	Coarse	Fine	Total	Coarse	Medium	Fine	Total	Silt	Clay	Total
0.0	0.0	1.0	1.0	0.3	1.7	6.0	8.0	64.6	26.4	91.0

D_{10}	D_{15}	D_{20}	D_{30}	D_{50}	D_{60}	D_{80}	D_{85}	D_{90}	D_{95}
	0.0014	0.0030	0.0061	0.0136	0.0204	0.0497	0.0586	0.0714	0.1199

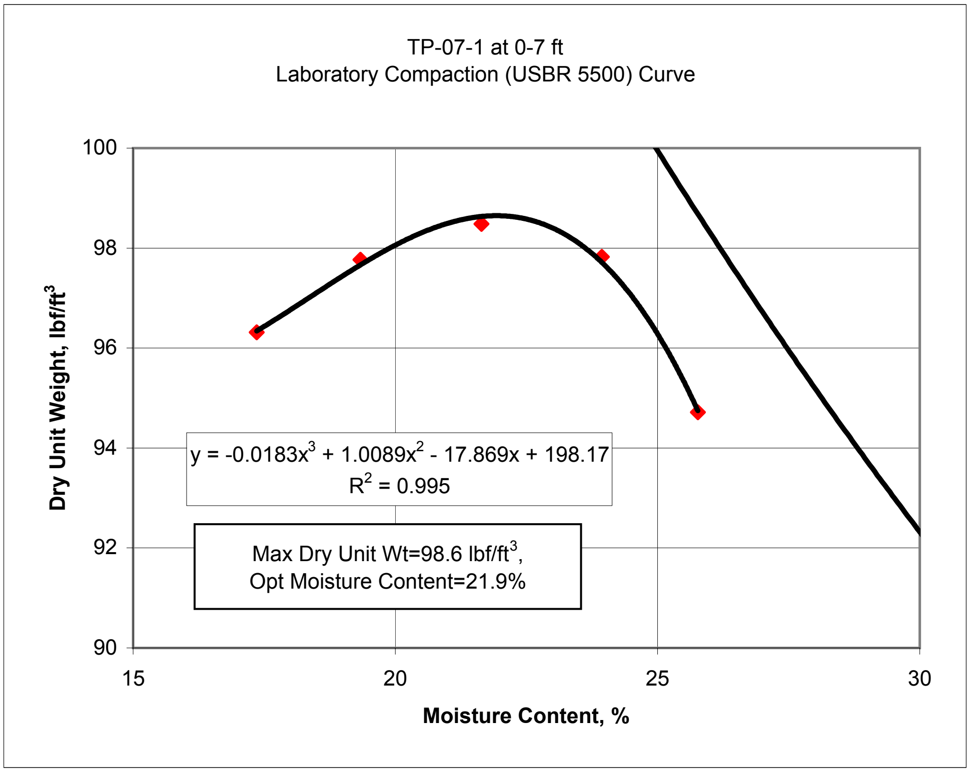
Fineness Modulus
0.16

Soil Consistency Test (Three-Point Liquid Limit Method)							
Sample No.	TP-07-1 at 0-7 ft						
Location	East Embankment						
Feature	Truckee Canal Breach						
Project	Newlands						
Date	2/19/2008						
Test	Plastic Limit		Liquid Limit				
Trial No.	1	2	1	2	3	4	
Dish No.	92	139	108	S-20	55	S58	
No. of blows	N/A	N/A	58	43	21	100	
Mass of dish+wet soil (g)	14.852	15.073	19.101	21.968	21.254	15.241	
Mass of dish+dry soil (g)	13.235	13.439	15.514	17.992	16.817	13.210	
Mass of dish (g)	6.267	6.416	6.333	8.166	6.326	7.710	
Mass of water (g)	1.617	1.634	3.587	3.976	4.437	2.031	
Mass of dry soil (g)	6.968	7.023	9.181	9.826	10.491	5.500	
% moisture	23.2	23.3	39.1	40.5	42.3	36.9	
Average plastic limit	23						

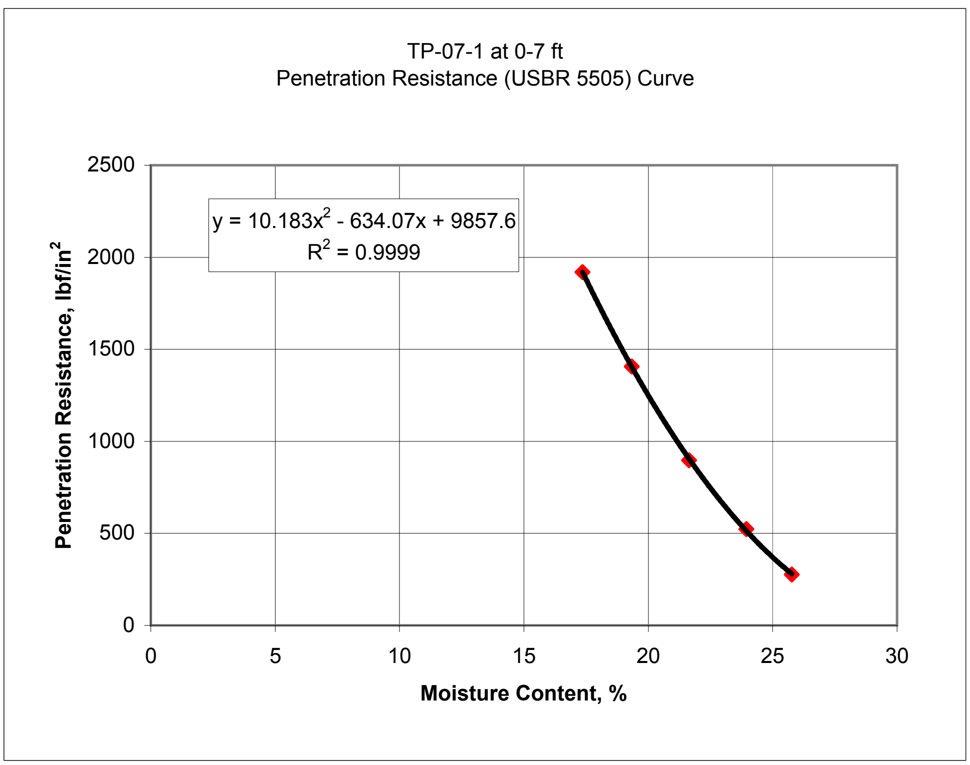
LL = 42 **PL = 23** **PI = 19** **Fi = -7.9**



Remarks:



TP-07-1 at 0-7 ft
Laboratory Compaction (USBR 5500) Curve
Dry Unit Weight, lbf/ft3
Moisture Content, %
100
98
96
94
92
90
15
20
25
30
y = -0.0183x3 + 1.0089x2 - 17.869x + 198.17
R2 = 0.995
Max Dry Unit Wt=98.6 lbf/ft3,
Opt Moisture Content=21.9%



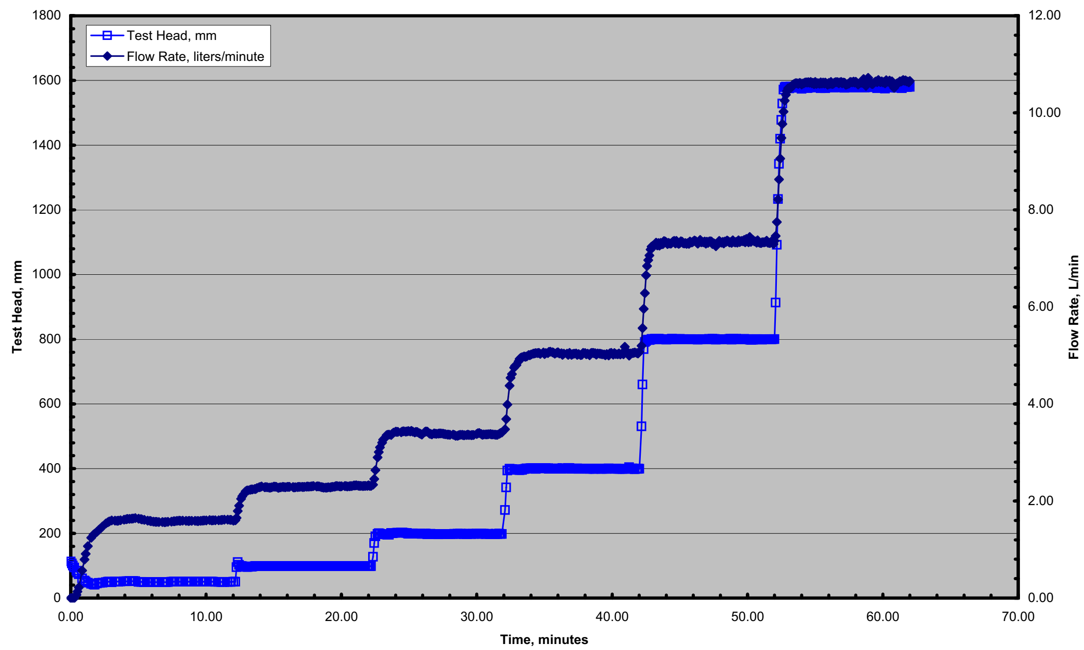
TP-07-1 at 0-7 ft
Penetration Resistance (USBR 5505) Curve
Penetration Resistance, lbf/in2
Moisture Content, %
2500
2000
1500
1000
500
0
0
5
10
15
20
25
30
y = 10.183x2 - 634.07x + 9857.6
R2 = 0.9999

Appendix B: Hole Erosion Test Data and Plots

Truckee Canal

Block 1 trimmed specimen   Test 1   02-05-2008

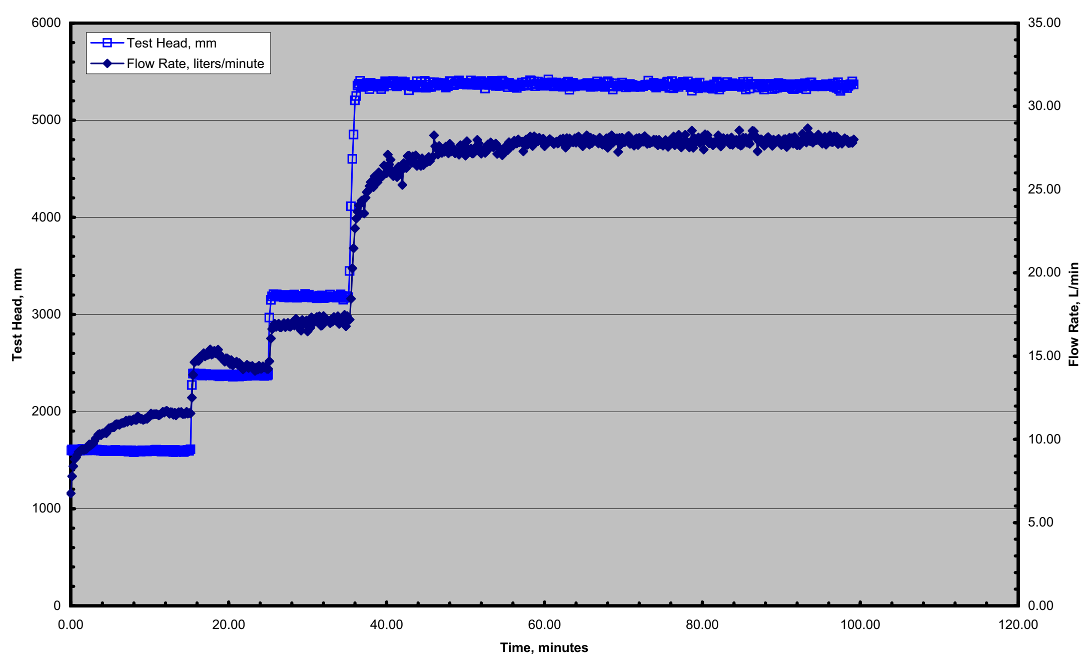
HET Test Record



Truckee Canal

Block 1   Test 2   02-19-2008

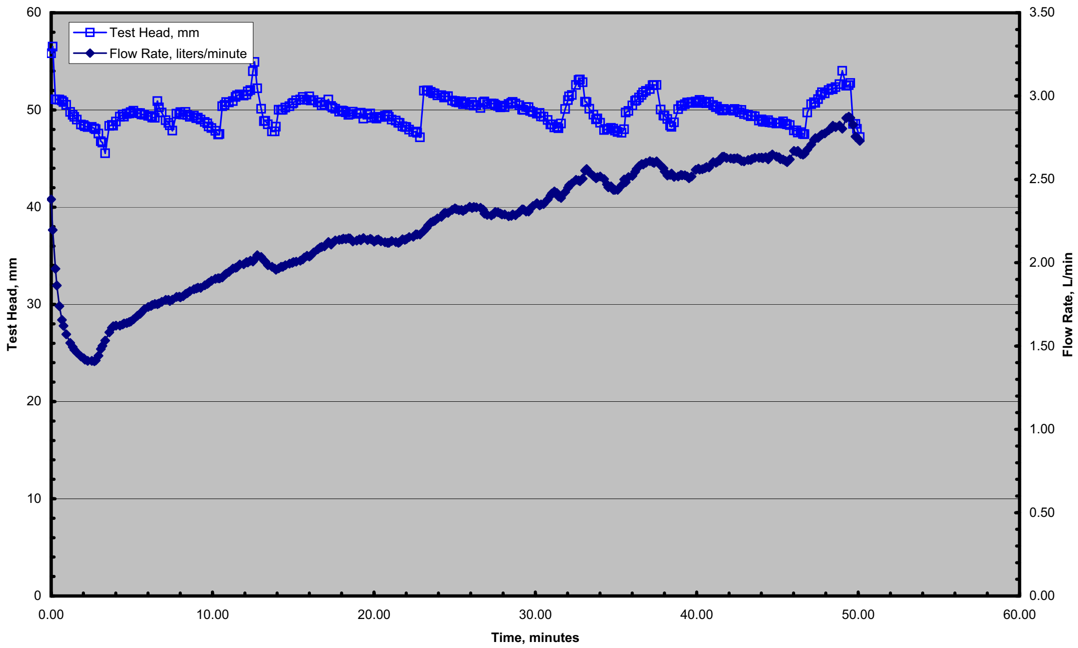
HET Test Record



Truckee Canal

Block 2 - undisturbed sample Test 1 02-06-2008

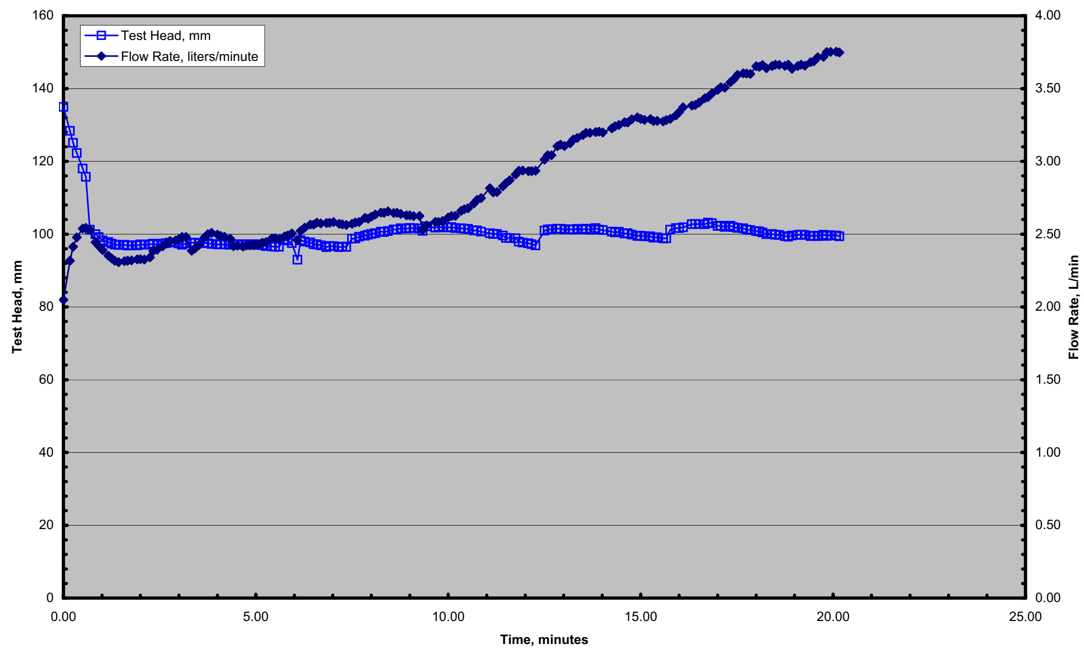
HET Test Record



Truckee Canal

Block 2 - 2nd trimmed sample Test 2 02-12-2008

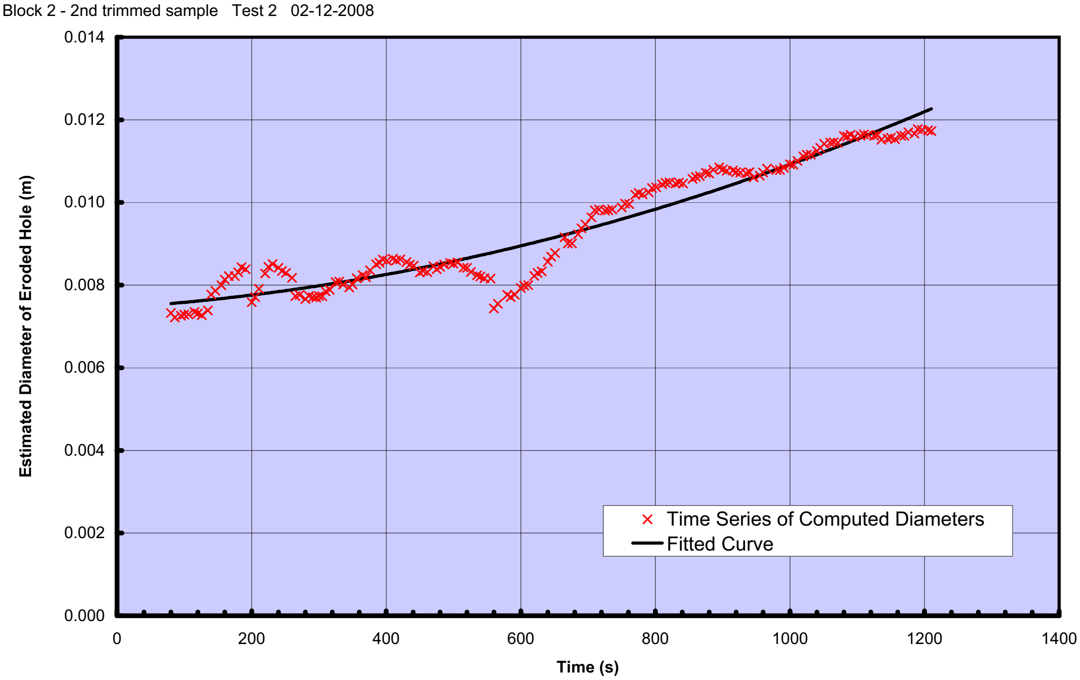
HET Test Record

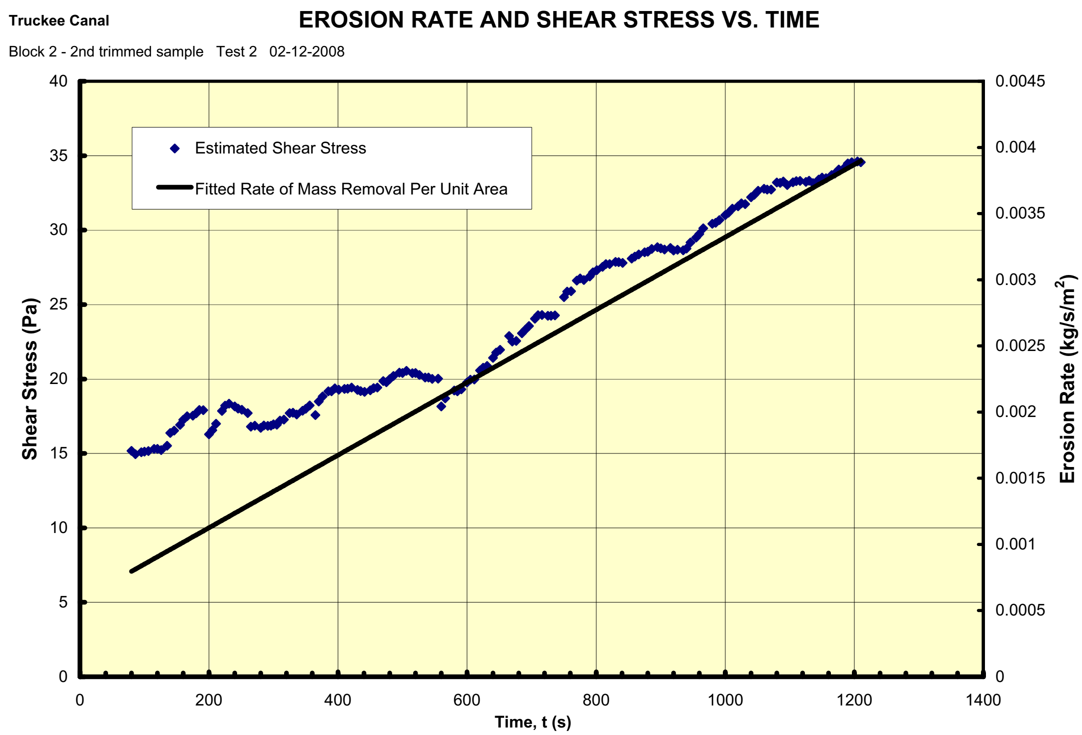


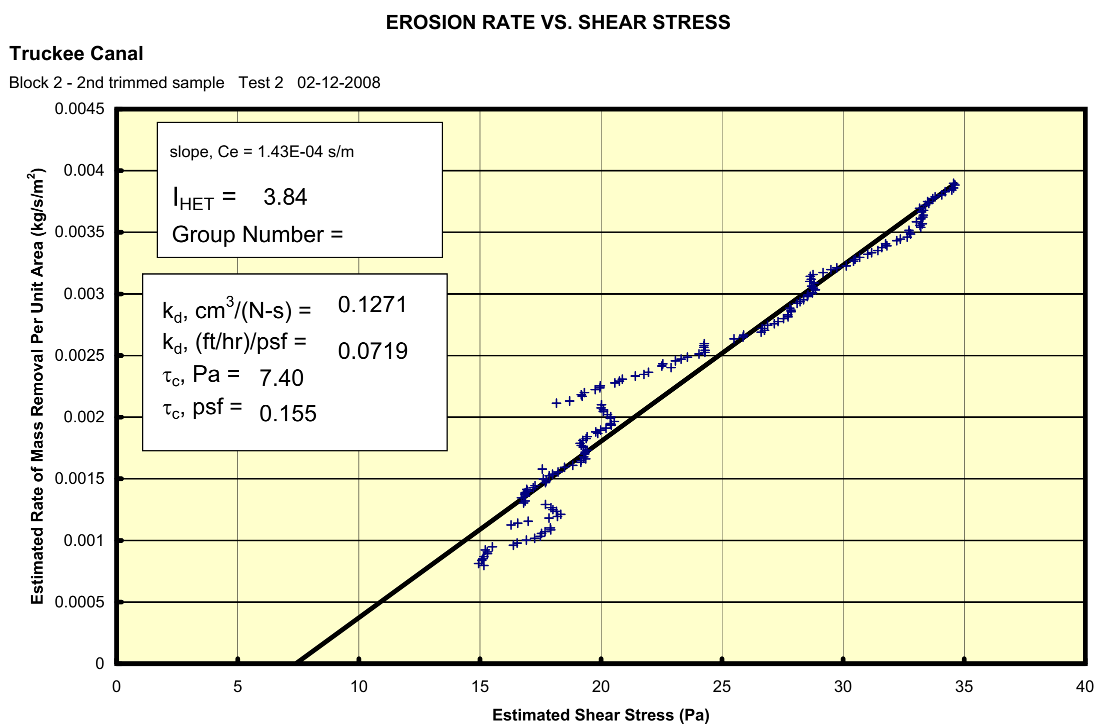
Truckee Canal

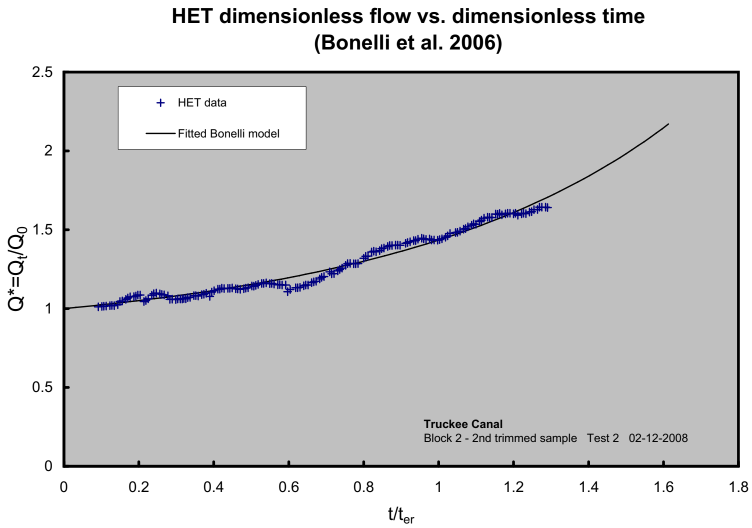
COMPUTED DIAMETER OF ERODED HOLE

Block 2 - 2nd trimmed sample Test 2 02-12-2008




Truckee Canal
EROSION RATE AND SHEAR STRESS VS. TIME
Block 2 - 2nd trimmed sample Test 2 02-12-2008
Estimated Shear Stress
Fitted Rate of Mass Removal Per Unit Area
Shear Stress (Pa)
Erosion Rate (kg/s/m2)
Time, t (s)


EROSION RATE VS. SHEAR STRESS
Truckee Canal
Block 2 - 2nd trimmed sample Test 2 02-12-2008
slope, Ce = 1.43E-04 s/m
I_{HET} = 3.84
Group Number =
k_d, cm^3/(N-s) = 0.1271
k_d, (ft/hr)/psf = 0.0719
τ_c, Pa = 7.40
τ_c, psf = 0.155
Estimated Rate of Mass Removal Per Unit Area (kg/s/m2)
Estimated Shear Stress (Pa)



Project	Truckee Canal
Feature	Block 2 - 2nd trimmed sample
Test	2
Date	1/0/1900

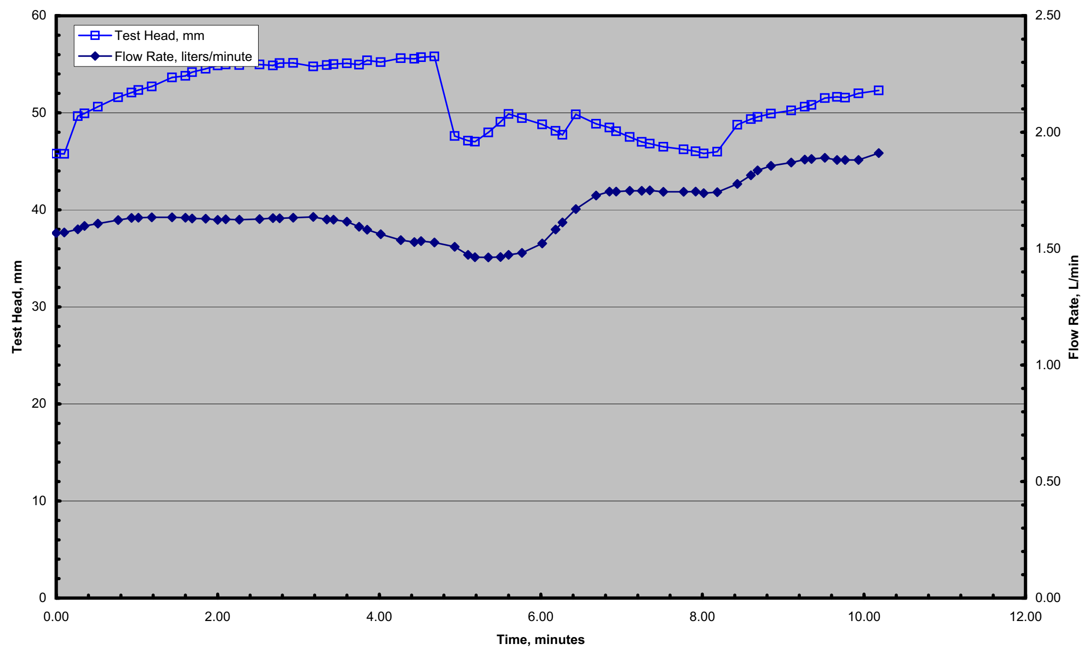
RESULTS SUMMARY

C_e	2.46E-04	((kg/s)/m^2)/Pa = s/m	
I_{HET}	3.61		**Group 3**
τ_c	14.1	Pa	
k_d	2.188E-07	m/s/Pa = m^3/(N-s)	
k_d	0.2188	cm^3/(N-s)	
k_d	0.1237	(ft/hr)/psf	
τ_c	0.29	psf	

Newlands, Truckee Canal Breach

TP-07-1 Test 1 09-26-2007

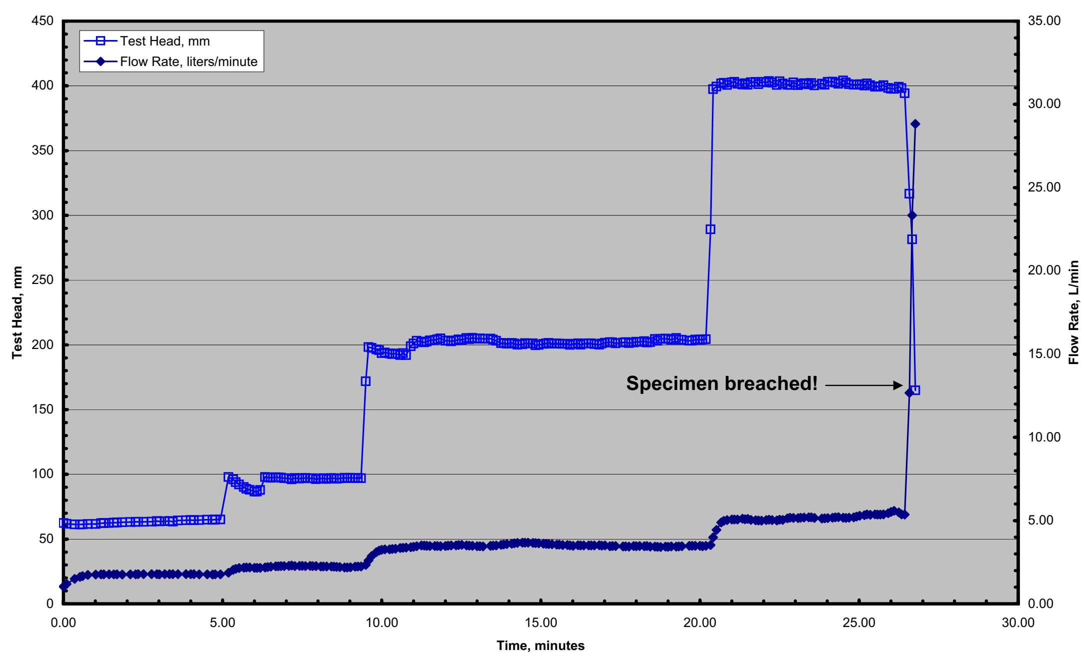
HET Test Record



Newlands - Truckee Canal

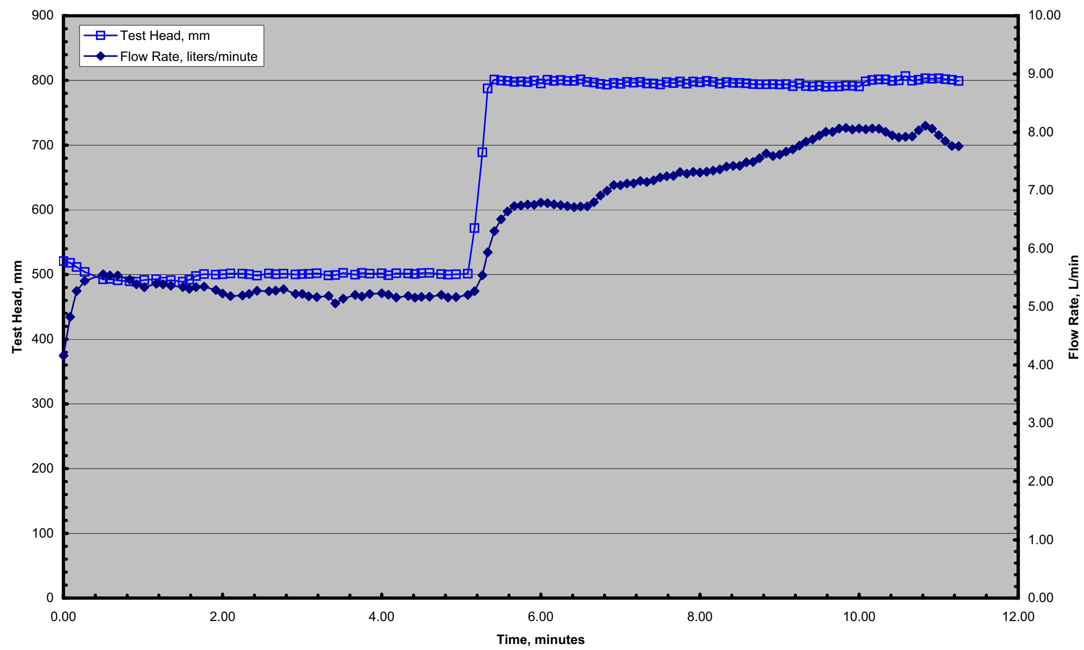
TP-07-1 Test 2 02-25-2008

HET Test Record



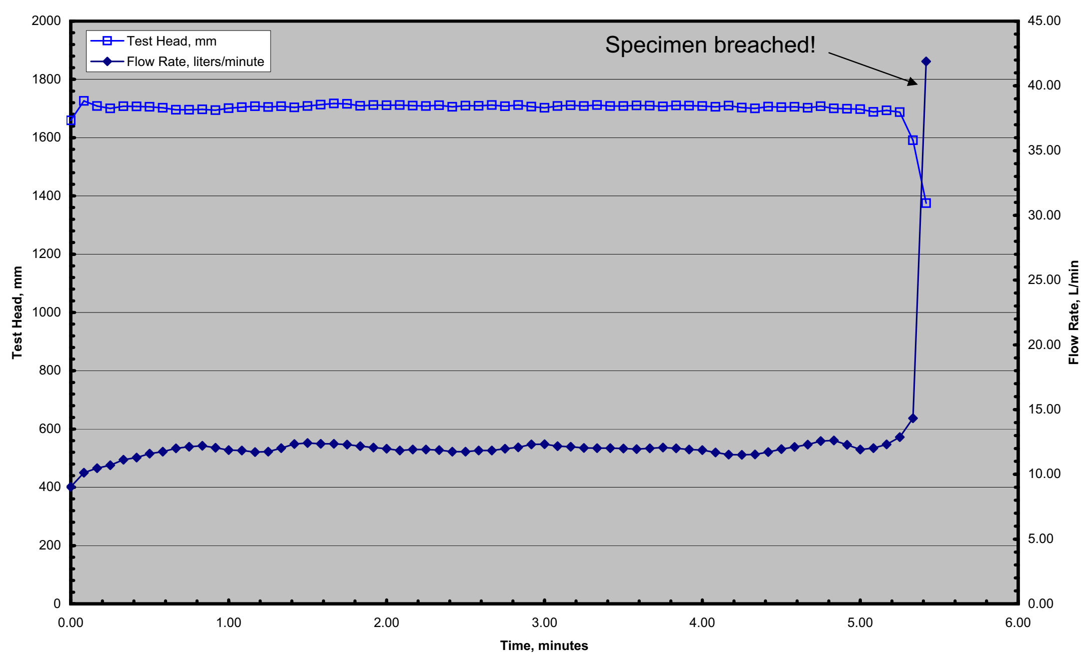
Truckee Canal
TP-07-1 Test 3 02-29-2008

HET Test Record



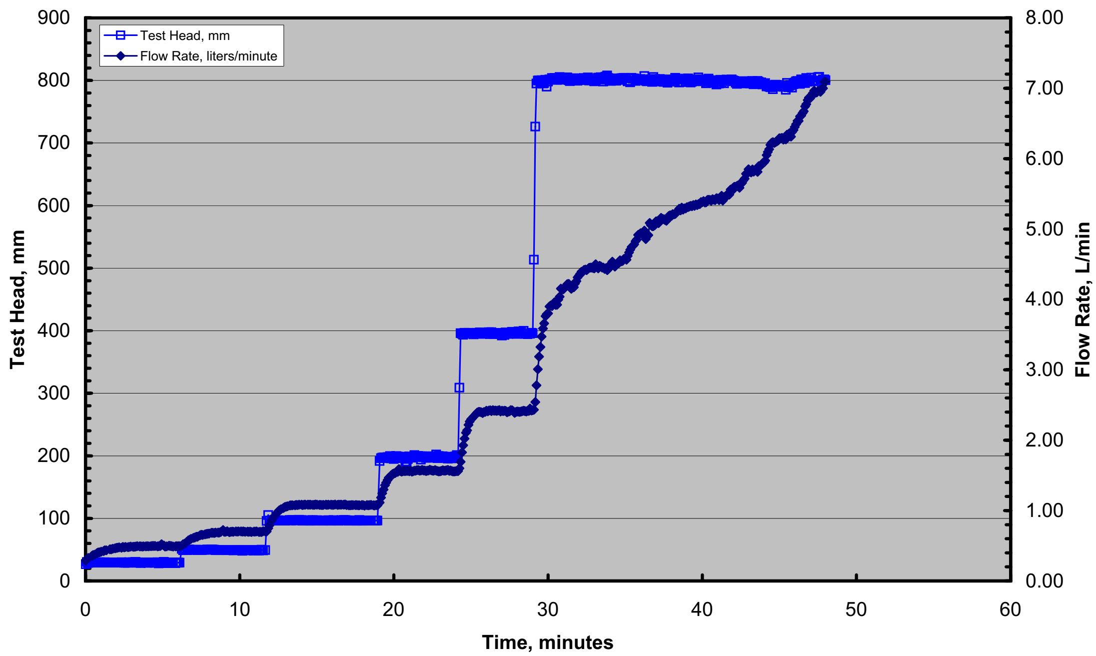
Truckee Canal
TP-07-1 Test 4 02-29-2008

HET Test Record



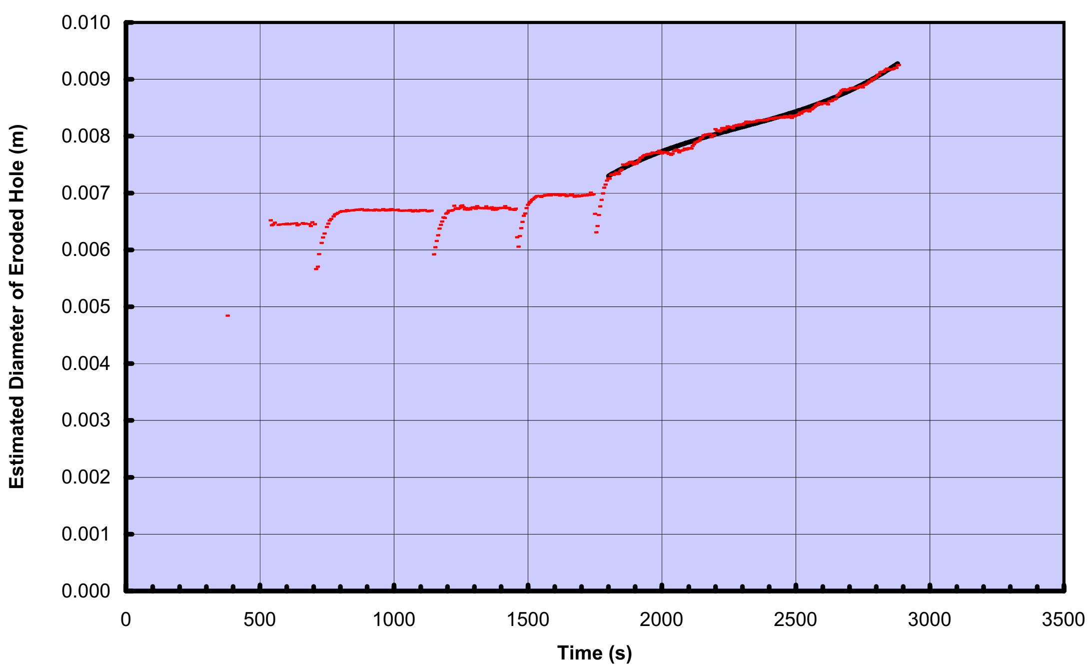
Truckee Canal
TP-07-4 Test 1 03-18-2008

HET Test Record



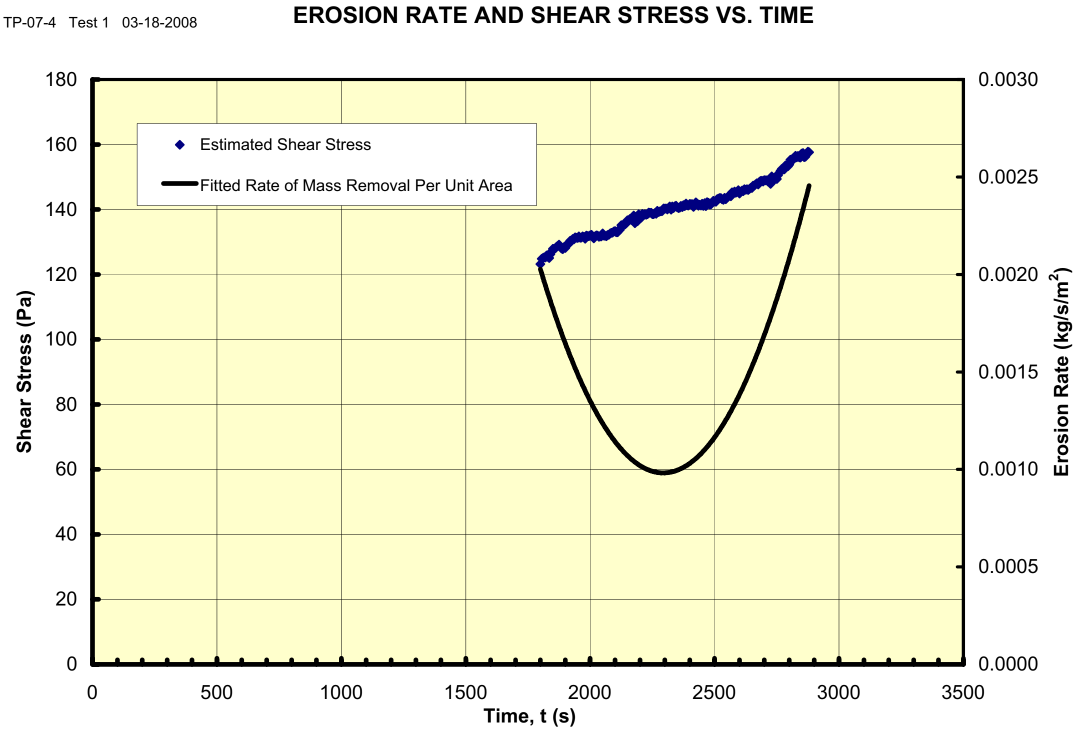
Truckee Canal
TP-07-4 Test 1 03-18-2008

COMPUTED DIAMETER OF ERODED HOLE



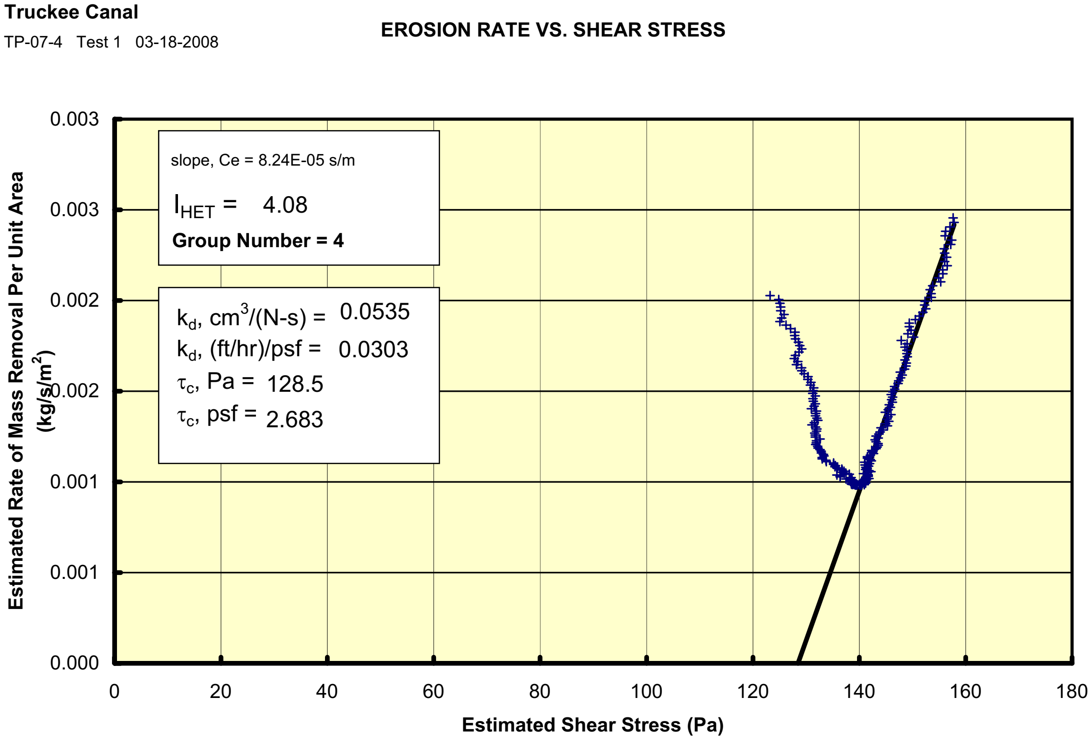
Truckee Canal

TP-07-4 Test 1 03-18-2008

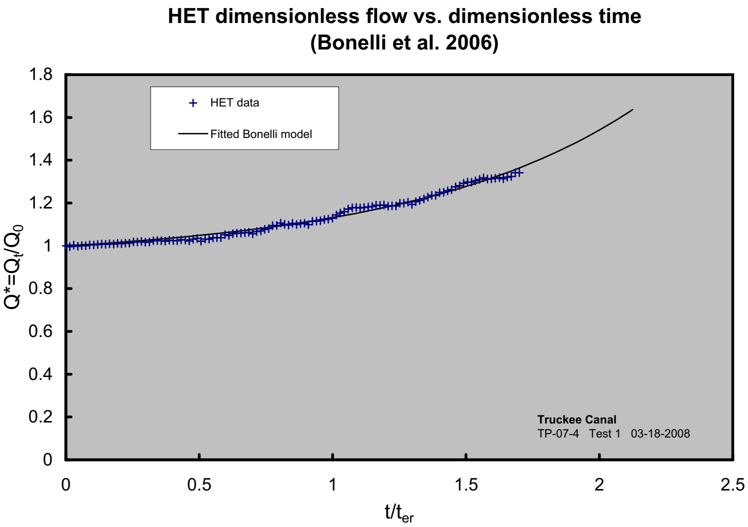


Truckee Canal

TP-07-4 Test 1 03-18-2008



HET dimensionless flow vs. dimensionless time (Bonelli et al. 2006)



Project Truckee Canal
Feature TP-07-4
Test 1
Date 3/18/2008

RESULTS SUMMARY

C_e	1.35E-04	((kg/s)/m^2)/Pa = s/m	
I_{HET}	3.87		**Group 3**
τ_c	136.0	Pa	
k_d	8.783E-08	m/s/Pa = m^3/(N-s)	
k_d	0.0878	cm^3/(N-s)	
k_d	0.0497	(ft/hr)/psf	
τ_c	2.84	psf	

Appendix C: Current Hole Erosion Test Procedures Used by the Bureau of Reclamation

The hole erosion test (**Wan and Fell 2004**) is one of several methods for evaluating the erodibility of cohesive soils. The HET utilizes an internal flow, similar to that occurring during piping erosion of embankment dams. A ¼-inch diameter hole is pre-drilled through a soil specimen and flow is passed through that hole under constant head. The head is increased incrementally until the threshold stress to initiate erosion is exceeded. Once erosion is initiated, the flow rate will accelerate over time, since enlargement of the hole leads to further increases in shear stress and higher rates of erosion. One must reach this “progressive erosion” condition in order to have a successful test.

An ASTM standard for the hole erosion test does not yet exist; in its absence, tests are performed and analyzed using methods consistent with those described by **Wan and Fell (2004)**. Recently, the Bureau of Reclamation and others have also investigated other methods for analyzing the data collected during HETs, focusing on the use of a piping erosion model developed by **Bonelli et al. (2006)**. The data reported here were analyzed using the **Wan and Fell (2004)** procedures, although they were also checked for consistency using the Bonelli method when applicable. The data analysis procedures are described below.

Test Facilities and Procedures

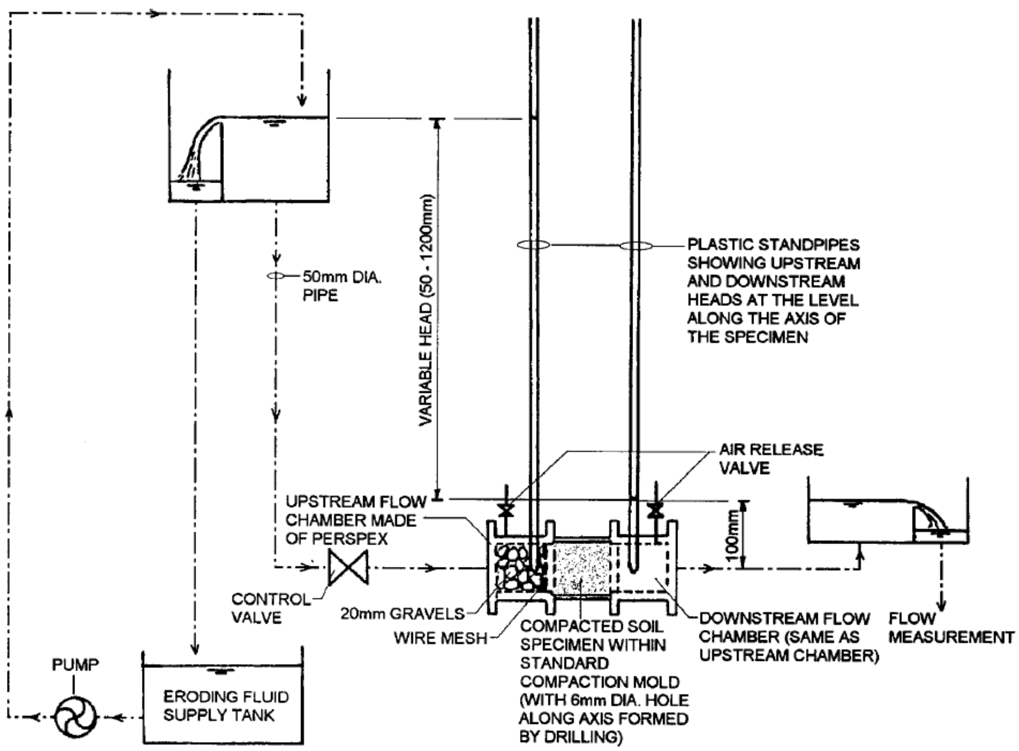


Figure C-1. Schematic diagram of hole erosion test facilities **(Wan and Fell 2004)**.

The hole erosion test facilities at the Bureau of Reclamation are similar to those used by **Wan and Fell (2004)**, except that the maximum head values in our two facilities are approximately 1600 mm and 5400 mm. Flow measurement is accomplished using 10° V-notch weirs, and data collection is automated using a computerized data acquisition system that records differential head and flow rate at 5 second intervals. The upstream and downstream chambers are similar to those shown in the schematic diagram. With erosion-resistant soils we have found no need for the 20 mm gravel in the upstream chamber. When testing very erosive soils we have found it helpful to place a plastic geotextile mesh fabric in the upstream chamber and protect the upstream and downstream faces of the compacted soil specimen with end plates. These end plates have an orifice opening varying from 10 mm to 25 mm, which allows some enlargement of the hole before the orifices begin to limit the flow rate.

The basic test procedure is as follows:

1. Following specimen preparation and compaction, specimens are sealed in plastic bags to prevent moisture loss and cured overnight before testing.
2. After curing, a ¼-inch diameter hole is drilled through the specimen using a drill press and wood auger bit to minimize compaction of the side walls of the hole. Drilling is performed at the slowest possible speed and the bit is advanced slowly and cleaned repeatedly during drilling.
3. The hole is cleaned using a 0.22-inch diameter rifle brush.
4. Specimens are installed into the apparatus with the original top surface (last compacted layer) upstream. If the soil is expected to be highly erodible, protective end plates are also installed.
5. The test facility is filled slowly with water and all air is bled from piezometer tubes connected to pressure sensors.
6. The water supply head tank is positioned to the desired starting head level. For specimens of unknown erodibility, tests are usually started at 50 mm of head.
7. The downstream weir box tank is filled with water to the level of the horizontal weir that maintains nearly-constant downstream head, and some additional water is then added to produce flow through the V-notch weir at a rate that approximates the expected starting flow rate. This is done in an attempt to have the test start with the weir box system in a state of flow rate equilibrium.
8. The data acquisition system is started and the inlet valve upstream from the test specimen is opened.
9. The flow rate is monitored to determine whether it is increasing or becoming steady. If the flow rate stabilizes at a given head, then the head tank is raised to increase the head.
10. When the flow rate begins to accelerate, the test head is maintained until at least several minutes of accelerating flow is observed. The operator should be mindful of the approximate maximum flow increase that can occur if end plates have been installed. For example, if 10 mm end plates have been installed, the ratio of flow rates with a 10 mm hole diameter to the flow through the original 6 mm diameter hole is approximately $(10/6)^2 \approx 3$. Thus, one should stop the test well before the flow rate has tripled from its value at the start of accelerating flow. If the test is allowed to continue too long, the orifice plate opening will begin to limit the flow rate which will affect the data analysis.

11. After the test is stopped, the upstream and downstream chambers are drained and the specimen is removed from the test facility. An initial visual estimate of the final hole diameter is made, and the specimen is weighed.
12. Specimens are oven-dried, weighed, and then a hydrostone casting is made of the erosion hole.
13. Hole diameters are determined from the casting, typically at 5 positions spaced approximately equally along the length. The length of the portion of the casting that is of relatively uniform diameter is also recorded. (Large scour holes at the upstream or downstream end are considered to reduce the effective length of the hole, which is taken into account in the data analysis.)

Wan and Fell analysis procedure

The deterministic data analysis method described by **Wan and Fell (2004)** attempts to compute changes in hole diameter at each time step at which data have been recorded. The computed time series of hole diameters can then be used to estimate the erosion rate and applied shear stress. Microsoft Excel spreadsheets are used to make the computations and present the data graphically.

The analysis begins by considering a cylinder of eroding fluid passing through the pre-drilled hole in a soil specimen. Assuming that over a short interval of time the flow is at steady state, the equation for force equilibrium is:

$$\tau \cdot P_w \cdot L = \rho_w \cdot g \cdot \Delta h \cdot \frac{\pi d^2}{4}$$

where:
τ = shear stress along the sides of the hole
P_w = perimeter of the hole
L = length of the hole
ρ_w = fluid density
g = acceleration due to gravity
Δh = head difference across the hole from upstream to downstream
d = diameter of the hole

For a laminar flow condition, the shear stress is expected to be proportional to the mean velocity of the flow

$$\tau = f_L \bar{v}$$

where
f_L = friction factor, S.I. units of kg/s/m
$\bar{v}$ = mean velocity of the flow, $Q/(\pi d^2/4)$
Q = flow rate

Combining these equations and solving for the friction factor yields:

$$f_L = \frac{\rho_w g}{Q} \frac{\Delta h}{L} \frac{\pi d^3}{16}$$

This equation can be used to solve for the friction factor at the start and end of the test, when the hole diameter, length, head differential and flow rate are all known. Research has shown that the friction factor varies in proportion the hole diameter, but the hole diameters during the test are not known until the analysis is complete, so the friction factor is instead assumed to vary during the test in proportion to the value of $(Q/\Delta h)^{1/3}$ for laminar flow, and $(Q^2/\Delta h)^{1/5}$ for turbulent flow. These quantities are surrogates for the hole diameter. The length of the erosion hole is assumed to vary linearly with time during the test (although it stays constant in many tests).

Denoting friction factors and hole lengths at intermediate times during the test by the subscript *t*, the same equations can be solved for the hole diameter to allow it to be computed throughout the test from measured values of the flow rate.

$$d = \left(f_{L_t} \frac{Q_t}{\rho_w g} \frac{L_t}{\Delta h_t} \frac{16}{\pi} \right)^{1/3}$$

If the flow is turbulent, the shear stress is proportional the square of the mean velocity and the following equations apply:

$$\tau = f_T \bar{v}^2$$

$$f_T = \frac{\rho_w g}{Q^2} \frac{\Delta h}{L} \frac{\pi^2 d^5}{64}$$

$$d = \left(f_{T_t} \frac{Q_t^2}{\rho_w g} \frac{L_t}{\Delta h_t} \frac{64}{\pi^2} \right)^{1/5}$$

Bonelli analysis procedure

Bonelli et al. (2006) proposed a universal model for piping erosion, applicable to analysis of the hole erosion test. They showed that the change in dimensionless hole radius is an exponential function of the dimensionless test time and the initial and critical shear stresses

$$\frac{R(t)}{R_0} = 1 + \left(1 - \frac{\tau_c}{\tau_0}\right)\left(e^{t/t_{er}} - 1\right)$$

where $R(t)$=radius at any time t and R_0=the initial radius at time zero, τ_c=critical shear stress, τ_0=shear stress at time zero, t=test time, and t_{er}=a characteristic erosion time scale for each test

$$t_{er} = \frac{2L}{k_d \gamma_w \Delta h} = \frac{2L\gamma_d}{C_e \gamma_w \Delta h}$$

where L=length of the hole, γ_w=unit weight of water ($\rho_w g$), Δh=head differential across the hole, γ_d=dry unit weight of soil, C_e=erosion rate coefficient (mass/time/area/stress), and k_d is a volumetric erosion rate coefficient (volume/time/area/stress).

The model assumes turbulent flow conditions and neglects any variation of the friction factor, the test head, or the length of the eroded hole. The method also presumes that the test data are collected entirely during the period of accelerating erosion. **Bonelli et al. (2006)** showed that the proposed model fit the observed hole radius data computed from 17 HETs performed by **Wan and Fell (2002)** using 9 different soils.

Recognizing that dimensionless discharge, Q^*, is proportional to the 2.5 power of the dimensionless radius (again neglecting effects of any change in the friction factor during a test), one can write

$$Q^* = \frac{Q(t)}{Q_0} = \left(\frac{R(t)}{R_0}\right)^{5/2} = \left[1 + \left(1 - \frac{\tau_c}{\tau_0}\right)\left(e^{t/t_{er}} - 1\right)\right]^{5/2}$$

Since flow rates are measured throughout a test and the initial shear stress is known from the starting hole diameter and flow rate, this model has only two unknown parameters, the erosion time scale, t_{er}, and the critical shear stress, τ_c. Using a non-linear optimization tool such as the Excel Solver, one can optimize these two parameters to obtain a best fit of the observed dimensionless values of discharge to predicted values computed for each dimensionless test time, t/t_{er}. The coefficient of soil erosion or the detachment rate coefficient can then be determined from the fitted value of the time scale factor, t_{er}. The significant advantages of this analysis method are the fact that the final hole diameter does not need to be measured, and the curve-fitting procedure minimizes the influence of short-term anomalies in erosion behavior during a test.

It should be emphasized that the formulation of the Bonelli model requires the fitted value of the critical shear stress τ_c to be less than the initial stress, τ_0, otherwise the quantity $(1-\tau_c/\tau_0)$ is negative. This means that tests must be conducted at a stress level that exceeds the critical stress and produces immediate progressive erosion, or one must customize the analysis to only examine the portion of the test in which the shear stress exceeds τ_c. If a test begins at a stress level that is slightly lower than the value needed to initiate progressive erosion, but the stress then increases due to cleanout erosion of material disturbed during hole drilling, the only way to accurately determine the critical stress would be to estimate the increase in hole diameter and shear stress that takes place leading up to the progressive erosion phase, then start the Bonelli analysis at that point in time. For this purpose, the Wan and Fell analysis procedure is still useful.

References

Bonelli, S., Brivois, O., Borghi, R., and Benahmed, N., 2006. On the modeling of piping erosion. *Comptes Rendus Mecanique* 334, Elsevier SAS, pp. 555-559

Wan, C.F., and Fell, R., 2004. Investigation of rate of erosion of soils in embankment dams. *Journal of Geotechnical and Geoenvironmental Engineering*, Vol. 130, No. 4, pp. 373-380.

Appendix D: Submerged Jet Erosion Testing of TP-07-1 and a Comparison to the Erodibility of Soils used in ARS Embankment Piping Breach Tests

Background – ARS Embankment Breach Research

The USDA-Agricultural Research Service has recently performed a series of large-scale outdoor embankment breach tests at their Hydraulic Engineering Research Unit at Stillwater, Oklahoma. These tests have considered breaches initiated by both overtopping and piping erosion. Most recently, three piping-initiated breach tests were performed, the last in the Fall of 2007.

Tested embankments were of homogeneous construction, utilizing three soils obtained from borrow areas or stockpiles on the laboratory grounds. Each embankment was constructed to a height of 4 ft with a 6 ft crest width and 3:1 upstream and downstream slopes (Fig. D-1). A 1.5-inch diameter pipe was embedded in each embankment and pulled out by a tractor to initiate each test. Each embankment impounded a small reservoir supplied continuously with flow from Lake Carl Blackwell (immediately upstream from the laboratory). A long-crested weir that bypassed excess flow around the test embankments allowed the reservoir level to be held approximately constant during the course of each test.

Figure D-1. — Piping test P1, 9 minutes after initiation of piping failure. Note that headcutting down to the base of the embankment is occurring simultaneously with enlargement of the piping hole, which was initiated at the elevation of the lower row of markers.

Table D-1 presents information on the soils used in each embankment and the results of each test. The tests and soils were designated P1, P2, and P3, and the breach times were approximately 0.23 hr, 17.2 hr, and 20.5 hr, respectively. For each embankment tested, submerged jet erosion tests were performed after the breach occurred. The table shows results of these tests.

The submerged jet erosion test (JET) was developed at the ARS laboratory **(Hanson and Cook 2004)**, to quantify erodibility of cohesive materials. The test is described in ASTM standard D 5852. It has been applied to erosion processes encountered in earth spillways, stream channel environments, and embankment dams. The test evaluates erodibility by attacking an exposed soil surface with a submerged water jet oriented normal to the surface. The depth of scour caused by the jet over time is used to estimate the parameters of a simple detachment-driven erosion equation:

$$\dot{\varepsilon} = k_d\left(\tau - \tau_c\right)$$

This equation is very similar to that used for the hole erosion test, except that $\dot{\varepsilon}$ is the volumetric rate of erosion, and the detachment rate coefficient, k_d, has units of volume per unit time per unit area, per unit stress. The volumetric approach is preferred because the jet test can be performed in the laboratory or in the field; in field situations the soil density may not be known, so it is more convenient to measure erosion volumetrically. In addition, the final modeling objective in most applications is to predict depth and breadth of erosion, for which a volumetric erosion model is most useful. The detachment rate coefficient and the erosion rate coefficient, C_e, used in the HET are related by the equation $C_e=k_d\rho_d$, where ρ_d is the dry density of the soil.

Ongoing research at the Bureau of Reclamation is studying whether the HET and JET produce equivalent rate coefficients (converted to the same mass or volumetric basis) and critical stress values when applied to similar soils. This research is showing that there is typically one to two orders of magnitude difference in the erodibility parameters, with the JET indicating that soils are more erodible. This is believed to be the result of several factors, including simplifications of the stress descriptions used to analyze both tests, different erosion mechanisms in the two tests, effects of the different geometry of the exposed surfaces in each test, and differences in the sensitivity of each test to variations in soil fabric or structure.

Hanson and Simon (2001) used the JET to study erodibility of cohesive streambeds in loess formations in the midwestern USA and proposed a relation between the critical shear stress and the detachment rate coefficient, $k_d = 0.2\tau_c^{-0.5}$, shown in Figure D-2. This line was a best fit to their data, but recent experience with jet erosion testing at Reclamation has shown that this line typically represents an erodibility envelope for the compacted engineering soils we have tested. Hanson and Simon also proposed a 5-level classification of soil erodibility, also shown on Figure D-1.

Jet Tests of TP-07-1

We were unable to run successful hole erosion tests on the TP-07-1 soil compacted to 80% of maximum dry density at 2% dry of optimum moisture content because the specimens were too weak. As an alternative, we performed two jet erosion tests on specimens compacted to those same approximate conditions. The first test was performed using a jet pressure of 12 inches of water, and the second test used a jet pressure of only 1.65 inches of water. Both tests yielded similar results, which are summarized in Table D-1 and plotted on Figure D-2. The figure also shows the results of the *in situ* jet tests conducted by ARS on their piping breach test embankments. The P-07-1 soil specimens are in the very erodible classification and have an erodibility that is approximately midway between the P1 and P2/P3 embankments tested by ARS. These embankments had erodibilities that are approximately two orders of magnitude apart in k_d, and their breach times were also about 2 orders of magnitude apart (0.2 hrs versus about 20 hours). This suggests that if an embankment of the same geometry as those tested by ARS was constructed from soil TP-07-1 with compaction conditions similar to those used for these jet tests, the breach time would be expected to be on the order of 2 hours.

References

Hanson, G.J., and Simon, A., 2001. Erodibility of cohesive streambeds in the loess area of the midwestern USA. *Hydrological Processes*, Vol. 15, pp. 23-38.

Hanson, G.J., and Cook, K.R., 2004. Apparatus, test procedures, and analytical methods to measure soil erodibility *in situ*. *Applied Engineering in Agriculture*, Vol. 20, No. 4, pp. 455-462.

Table D-1. A Comparison of USBR Truckee Canal Embankment Breach JET Tests and *in-situ* JET Tests Associated with ARS Piping Breach Tests.

USBR Laboratory Jet Test Results

Soil Sample	USCS Classification	LL	PI	Jet Erosion Test Sequence Number	Compaction Moisture Content	Compaction Effort		Dry Unit Weight	Laboratory Jet Erosion Test Results		Relative Compaction
					%	blows / layer	ft-lbf/ft^3	lbf/ft^3	k_d cm^3/(N-s)	τ_c (Pa)	
Truckee Canal TP-07-1 at 0-7 ft	CL	42	19	JET1	20.5	5	2475	82.3	20.0	0.028	83.1%
				JET2	20.5	5	2475	81.6	30.8	0.078	82.4%

ARS Piping Breach Tests and *in situ* Jet Erosion Tests (preliminary data provided by Greg Hanson and Sherry Hunt, USDA-ARS)

Embankment	USCS Classification	LL	PI	Optimum Moisture Content	$\gamma_{d,max}$	Compaction Moisture Content	Compaction Effort (estimated)	Dry Unit Weight	Relative Compaction	*in situ* Jet Erosion Test Results		Piping Test Breach Time[a]
				%	lbf/ft^3	%	ft-lbf/ft^3	lbf/ft^3	%	k_d cm^3/(N-s)	τ_c (Pa)	hrs
ARS Piping Test P1	SM	---	NP	11.0	113.2	11.5	4000-6000	105.9	93.5%	150	0.00	0.23
ARS Piping Test P2	CL-ML	21	7	11.5	117.9	12.7	4000-6000	109.0	92.5%	2.0	2.5	17.2
ARS Piping Test P3 - lower lifts	CL	28	13	12.9	112.3	16.5	4000-6000	111.4	99.2%	0.17	22	---
ARS Piping Test P3 - upper lifts	CL	28	13	12.9	112.3	15.1	4000-6000	110.9	98.7%	1.2	4.6	20.5[b]

Notes

a) Time required for collapse of soil arch over the eroding pipe, which marks the approximate completion of initial breach formation and the beginning of lateral widening of the breach

b) Internal erosion growth in embankment P3 occurred in the upper layers

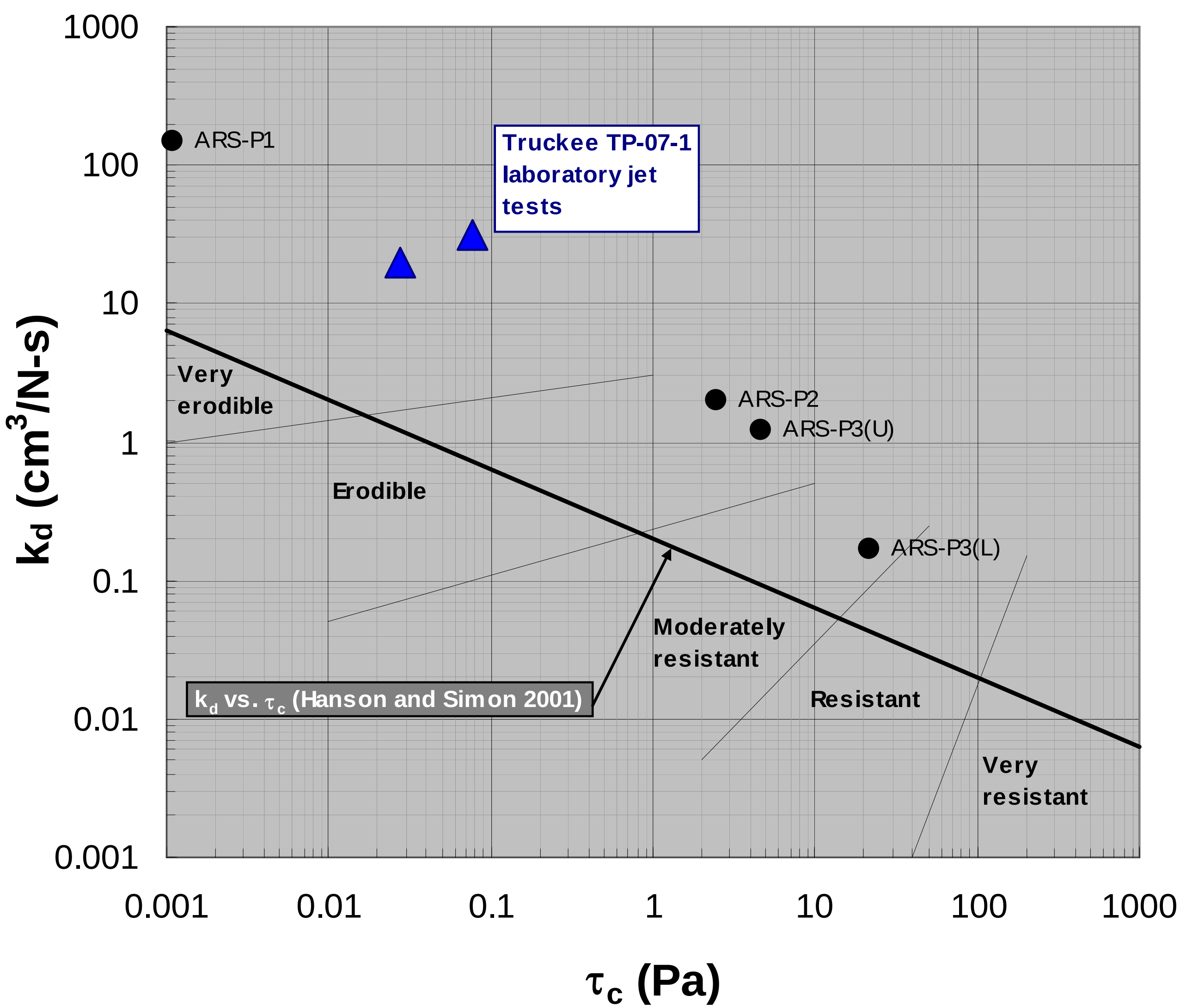


Figure D-1. — Laboratory jet test results for TP-07-1, *in situ* jet test results for ARS piping breach test embankments, and erodibility classifications and erosion rate-critical shear relation proposed by Hanson and Simon (2001).

SUBMERGED JET TEST DATA

DATE 3/14/2008

JET TEST LOCATION Truckee TP-07-1

OPERATOR TLW

ZERO POINT GAGE READING (on deflector plate) 0.980

TEST # 1

PRELIMINARY HEAD SETTING (IN.) 12

POINT GAGE RDG @ NOZZLE 1.017

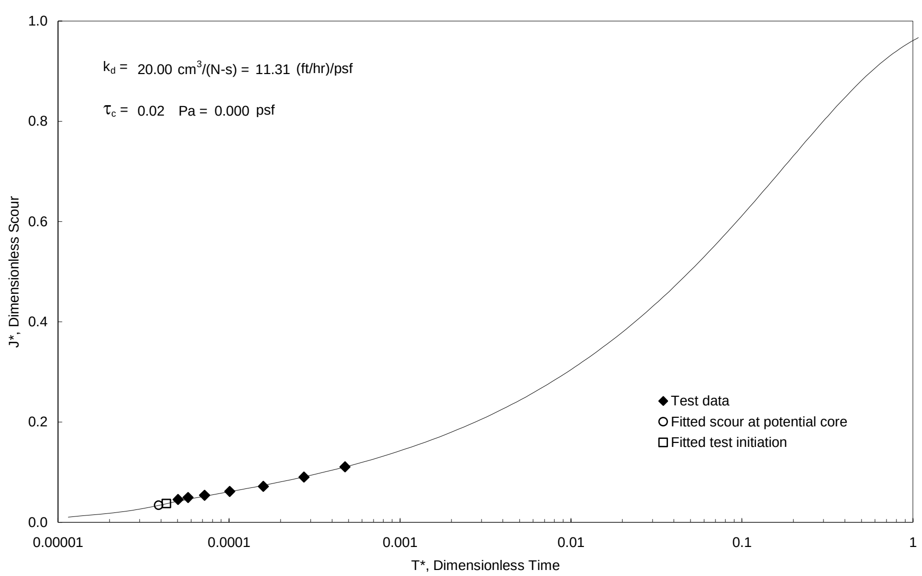
NOZZLE DIAMETER (IN.) 0.25

INITIAL NOZZLE HEIGHT (FT) 0.145

SCOUR DEPTH READINGS			
TIME (MIN)	DIFF TIME (MIN)	PT GAGE READING (FT)	MAXIMUM DEPTH OF SCOUR (FT)
0		0.873	0.000
0.25	0.25	0.841	0.032
0.5	0.25	0.825	0.048
1	0.5	0.809	0.064
2	1	0.778	0.095
4	2	0.739	0.134
8	4	0.668	0.205
15	7	0.588	0.285

HEAD SETTING	
TIME (MIN)	HEAD (IN.)
0	12.00
0.25	12.00
0.5	12.00
1	12.00
2	12.00
4	12.00
8	12.00
15	12.00

Dimensionless Scour vs. Dimensionless Time (Blaisdell Method)



SUBMERGED JET TEST DATA

DATE 3/14/2008

JET TEST LOCATION Truckee TP-07-1

OPERATOR TLW

ZERO POINT GAGE READING (on deflector plate) 0.980

TEST # 2

PRELIMINARY HEAD SETTING (IN.) 1.65

POINT GAGE RDG @ NOZZLE 1.017

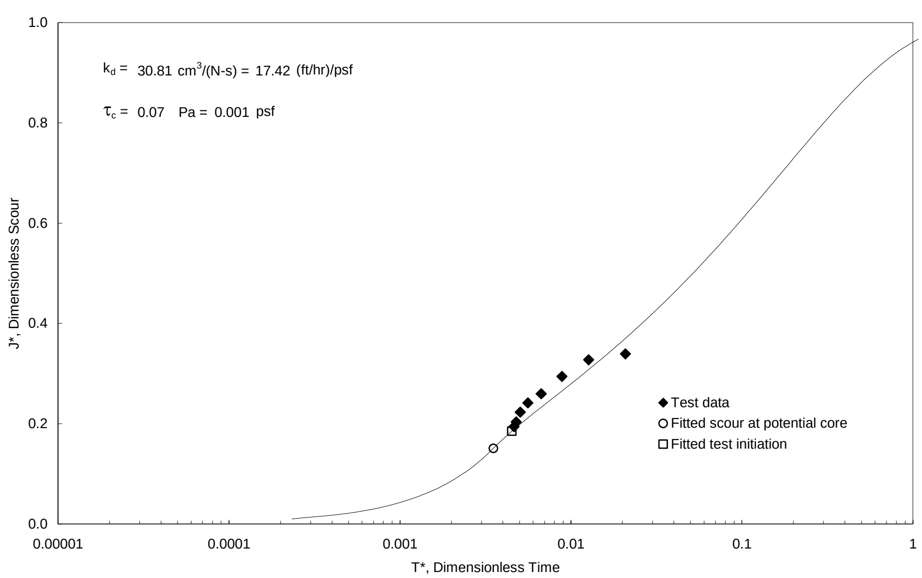
NOZZLE DIAMETER (IN.) 0.25

INITIAL NOZZLE HEIGHT (FT) 0.161

SCOUR DEPTH READINGS			
TIME (MIN)	DIFF TIME (MIN)	PT GAGE READING (FT)	MAXIMUM DEPTH OF SCOUR (FT)
0		0.856	0.000
0.25	0.25	0.848	0.008
0.5	0.25	0.840	0.016
1	0.5	0.823	0.033
2	1	0.807	0.049
4	2	0.791	0.065
8	4	0.761	0.095
15	7	0.732	0.124
30	15	0.722	0.134

HEAD SETTING	
TIME (MIN)	HEAD (IN.)
0	1.65
0.25	1.65
0.5	1.65
1	1.65
2	1.65
4	1.65
8	1.65
15	1.65
30	1.65

Dimensionless Scour vs. Dimensionless Time (Blaisdell Method)



(a)

(b)

Figure D-3 (a) and (b) – Post-test photos of TP-07-1 JET 2 specimen, after oven drying. This test used a jet pressure of only 1.65 inches of water.